



International Forum

Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry

**February 10-12, 1998
Pacific Forestry Centre
Victoria, British Columbia
Canada**

**Proceedings compiled and edited by
D.A. Hill and D.G. Leckie**



**Natural Resources
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Natural Resources Canada
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FOREWORD

The "International Forum on Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry" was a forum of papers and discussion sessions on computer-assisted methods of forest interpretation and parameter extraction from high resolution (≤ 1 m) digital imagery. Data sources included; airborne digital frame cameras, multispectral imagers, imaging spectrometers, digitized aerial photography, videography, and next generation high resolution satellite imagery. There were over 100 participants drawn from scientists, technology developers, remote sensing industry, forestry practitioners, and forest managers. Concentration was on forestry requirements, current capabilities, and future activities. The intent was to disseminate knowledge on techniques and applications, foster cooperation among investigators, and encourage interaction among technology developers and practitioners.

The forum consisted of a series of technical sessions with presented papers. Each session concluded with an open discussion on the topic. The session topics were:

- Single Tree Isolation,
- Regeneration and Forest Health,
- Species Classification,
- Stand Structure, Crown Closure and Gaps,
- Computer-assisted Interpretation Systems,
- Other Applications.

The stage for the forum was set by brief talks presenting the "Challenge and the Reality". These were given by Dave Gilbert (Director, Resources Inventory Branch, British Columbia Ministry of Forests (BCMOF)), Bill Waugh and Pat MacDonell (MacMillan Bloedel Ltd.), and Dr. Paul Addison (Director General, Pacific Forestry Centre, Canadian Forest Service). These presenters gave, from a broad perspective, the potential role of automated high resolution technology, the milieu into which it fits (organizational, political, financial, and technological) and the reality of implementing the technology. Presentations were also given summarizing the forestry requirements in terms of large area inventories, local government forest managers, forest industry, national inventories, carbon budget, ecological and socio-economic applications, and criteria and indicators for sustainable forest management. Presenters were Tim Salkeld (BCMOF, Resources Inventory Branch), Jeff Beale (BCMOF, Robson Valley Forest District), Bill Waugh and Pat MacDonell (MacMillan Bloedel Ltd.), Axel Pinz (Graz University of Technology, Austria), and Peter Hall (Canadian Forest Service, Science Branch). There was an ad hoc session where current and new initiatives were presented, plus a concluding session.

The Forum was sponsored by MacMillan Bloedel Limited, the British Columbia Ministry of Forests, and the Canadian Forest Service. Funding was also provided by the Province of British Columbia through the Forest Renewal British Columbia program. The organizing committee was led by Don Leckie and David Hill (Canadian Forest Service (CFS), Pacific Forestry Centre), Ian Chong and Cara Jay (MacMillan Bloedel Ltd.), and John Wakelin (BCMOF). Francois Gougeon, Nick Walsworth, and Murray Strome (CFS), Graeme Weir, Xiaoping Yuan, and Mark Gillis (BCMOF) assisted in planning and executing the forum. Charles Burnett, Joanne White, Scott Allen and Sara Adams (University of Victoria, Geography Dept.) assisted in providing audio visual support for the forum. Geri O'Hara, Darlana Ball and many others at CFS-Pacific Forestry Centre aided with the preparation and logistical support of the forum.

The forum indicated that automated interpretation of high spatial resolution digital data for forestry, although in the "pioneering stage", is alive, well and growing. It is a field of study within which there are many active subfields. This field is supported by eager and cooperative forestry clients with varied and important applications niches, but with real constraints. Along with these clients, there is also an sophisticated and progressive service supply industry.

We hope this proceedings will provide a good compendium of past, present and potential future work, lead readers to a better understanding of the current state of the art, provide insight to future developments, and contribute to the advancement of the technology and implementation of its applications.

Donald G. Leckie
David A. Hill

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Single Tree Isolation



AUTOMATIC INDIVIDUAL TREE CROWN DELINEATION USING A VALLEY-FOLLOWING ALGORITHM AND A RULE-BASED SYSTEM

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ABSTRACT

In remotely sensed aerial images or digitized aerial photographs of high spatial resolution (10-100 cm/pixel) tree crowns are typically visible as almost distinct items. To produce semi-automatic forest inventories from such data (even stand-based inventories), it is better for the computer to deal directly with this predominant structural element of the images. A first obvious step is thus, the delineation of the individual tree crowns, preferably in a completely automatic fashion. This step is to be followed by an individual tree crown species recognition and then, a regrouping (if needed) into relatively conventional forest stands. Such a comprehensive approach can provide very detailed forest inventories, specially considering that regroupings can be organized to follow criteria other than that of the present inventories. This paper addresses the automatic individual tree crown delineation process.

The individual tree crown delineation is accomplished by first following the valleys of shade that typically exist between the crowns of dense forest stands. The image from a selected spectral band is first smoothed. Areas that are completely in the shade are masked out by thresholding and local minima are found in the remaining areas, except for non-forested areas that were masked out a priori. From the local minima, valleys are followed to other local minima. Visually, this delineates most coniferous tree crowns rather well. However, not all tree crowns are fully delineated and tree clusters still exist, but most importantly, the process does not yet have the concept of tree crowns as distinct elements. This "awareness" is made possible by the subsequent use of a rule-based system which attempts to follow in a clock-wise fashion the internal boundaries of each individual tree crown (ITC) until a distinct closed area is obtained. Additional rules attempt to recognize tree clusters and separate them into ITCs. From there, additional ITC-based processes, such as an ITC-based classifier (Gougeon *et al.*, 1988), are used to produce detailed information about the given forested area.

This paper will first describe briefly the valley-following algorithm and the rule-based system and then, comment on their strengths and weaknesses, and potential remedies to these weaknesses. Examples will be shown throughout. The paper concludes with a list of possible improvements and future developments.

Keywords: forest inventory, computer image analysis, individual tree crown, crown delineation, valley following, rule-based approach, ITC.

RÉSUMÉ

DÉLIMITATION AUTOMATIQUE DES HOUPPIERS À L'AIDE D'UN ALGORITHME DE DÉFINITION DE ZONES D'OMBRE ET D'UN SYSTÈME À BASE DE RÈGLES

Sur les images aériennes obtenues par télédétection ou sur des photographies aériennes prises à haute résolution spatiale et numérisées (10-100 cm/pixel), les houppiers des arbres se dessinent presque aussi nettement que s'il s'agissait d'éléments distincts. Pour produire des inventaires forestiers de façon semi-automatique à partir de telles données (même les inventaires basés sur les peuplements), il est préférable que l'ordinateur traite directement avec cet élément structurel prédominant des images. Une des premières étapes consiste évidemment à délimiter les houppiers, de préférence en mode complètement automatique. Cette étape doit être suivie d'une identification individuelle des espèces de houppiers et, ensuite, d'un regroupement (au besoin) en peuplements forestiers relativement conventionnels. Une telle approche approfondie peut permettre de constituer des inventaires forestiers très détaillés, surtout si l'on considère que les regroupements peuvent être organisés de manière à respecter des critères autres que ceux qui servent à établir les inventaires actuels. Ce document traite donc du processus de délimitation automatique des houppiers.

On commence la délimitation des houppiers en suivant les zones d'ombre qui se profilent généralement entre les houppiers des peuplements forestiers denses. L'image obtenue d'une bande spectrale choisie est d'abord ajustée. Les zones se trouvant complètement dans l'ombre sont masquées par un seuillage, et on trouve les valeurs minimales locales dans les autres zones, sauf pour les secteurs non boisés qui avaient été masqués au départ. À partir des valeurs minimales locales, on suit les zones d'ombre jusqu'à une autre valeur minimale locale. Sur le plan visuel, cette démarche permet de délimiter avec une bonne précision la plupart des houppiers des conifères. Cependant, certains houppiers échappent à la délimitation intégrale et il reste encore des grappes d'arbres ici et là, mais il faut absolument souligner que le procédé n'est pas encore à l'étape de la délimitation des houppiers comme éléments distincts. Cette étape est toutefois rendue possible par l'utilisation subséquente d'un système à base de règles qui tente de suivre dans un mouvement horaire les limites intérieures de chaque houppier jusqu'à l'obtention d'une zone fermée distincte. En ajoutant d'autres règles, on tente d'identifier des grappes d'arbres et de les séparer en houppiers distincts. De là, on utilise d'autres procédés basés sur la délimitation des houppiers, comme un classificateur du même type (Gougeon et coll., 1988), pour produire de l'information détaillée sur la zone forestière à l'étude.

Dans le présent document, l'auteur décrit d'abord brièvement l'algorithme de définition des zones d'ombre et le système à base de règles, il commente ensuite sur leurs points forts et leurs points faibles et propose des solutions pour remédier à ces faiblesses. Des exemples servent à appuyer ses propos. L'auteur conclut avec une liste d'améliorations possibles et de développements futurs.

INTRODUCTION

The spatial resolutions of images available from multispectral airborne sensors, digitized aerial photographs and upcoming earth observation satellites imply a change in the digital image analysis paradigm for forestry. With the increased level of details, individual tree crowns are now visible. The forest stand based approaches relying on pixel-based classifications at low spatial resolutions (10-100 m/pixel) and area-based texture segmentations at medium resolutions (1-10 m/pixel) get increasingly inappropriate. At high resolutions (10-100 cm/pixel), it is better to deal directly with the essential structural element of the forest stands: the individual tree crown (ITC).

The ITC approach consists of separating the crowns from one another and from the background vegetation, recognizing one by one their species and, if needed, regrouping them into forest stands. It could enable the production of semi-automatic forest inventories from digital remote sensing data. The species composition of these automatically generated stands (or even existing stands) would be known with an increased level of precision. However, such an approach gathers additional importance when taking into consideration the fact that modern forest management inventories, meant to manage the forest resource in

accordance with much stricter rules taking biodiversity, wildlife, environmental and recreational concerns into account, require even more details than what is currently available. Additional forestry parameters such as tree crown areas, canopy closure, stand density, non-forested gap distribution, etc., are also easily obtained for each stand. The ITC approach also offers the capability to retain the specific individual tree-based information. This could be particularly useful for silviculture treatments, selective cuts, biodiversity assessments, and other applications.

The first obvious step in this ITC-based approach is the delineation of the individual tree crowns, preferably in a completely automatic fashion. This is accomplished by first following the valleys of shade that typically exist between the crowns of moderate to dense forest stands. Then, a rule-based system is used to further delineate the tree crowns. This paper will first describe briefly these two processes and then comment on their strengths and weaknesses. The paper concludes with plans for further testing and improvements in the coming years.

INDIVIDUAL TREE CROWN ISOLATION

Although perceived as uninteresting background information, one of the important image features that allows humans to detect individual trees in average to dense coniferous stands on aerial photographs or high resolution multispectral aerial images is the presence of thin bands of shade separating the crowns. The automatic "valley following" isolation process uses the same feature. The idea behind the process, following the valleys of shade in a grey-level image, can be easily conveyed by a geographical/topographical analogy (Figure 1). From an illumination point of view, the bright individual tree crowns in an image appear like mountains (i.e., high pixel values). The darker areas surrounding them, the shaded lower branches and understory, appear like valleys (i.e., low pixel values). Furthermore, the mountains may have well lit sides and shaded sides, like mountains at low sun elevation (e.g., sunset), but fortunately, the valleys are typically slightly darker. By following the continuum of locally darkest areas of a grey-level image, the process ends up isolating most of the individual tree crowns from each other and from the background shaded vegetation.

Before using the "valley following" isolation process, some preprocessing is typically required. Firstly, if using a digitized colour aerial photo or a multispectral image, a selection must be made of the appropriate grey-level image (i.e., spectral band) to use. This image is then referred to as the "illumination" image. For general forest inventory purposes, a near infrared band is typically used because of its sensitivity to illumination variations and its good response to vegetative material. However, if defoliated trees are of interest, one of the visible bands is typically more appropriate since tree branches and bark produce low responses in the near infrared part of the spectrum. It is also possible to combine the potentially different information available from the various spectral bands by using processes such as "principal component" (Richards, 1986) or "Intensity-Hue-Saturation" transformations (Lillesand & Kiefer, 1994). Secondly, unless the illumination image selected comes from a transformation, the selected image is typically smoothed by a filtering process. This removes some of the natural variability of the data and alleviates some potential difficulties in isolating tree crowns. It also minimizes problems that may be due to sensor (or digitization) noise, noise that is specially prominent in the shaded parts of images. It may also help with the occurrences of branches sticking out of one crown and reaching another one. In addition, depending on the spatial resolution of the image, a stronger smoothing filter may be used and still produce beneficial effects. It could alleviate difficulties related to having too much detail within the crowns, for example, large branches that may have their own shadow within the crown or any self-shaded areas within the lit side of crowns. Thirdly, non-forested areas and forested areas that do not respect the premise of having bands of shade separating their tree crowns should be removed or masked out. This can be accomplished by manually delineating these areas to create a mask or, more often than not, by running a generic pixel-based unsupervised classification and selecting appropriate classes that will be merged into a single mask.

The first step in the "valley following" process involves a threshold that is used to eliminate a priori large shaded areas. These areas, that can be visualized as plateaus within the valleys of shade, are not well suited for an algorithm meant to follow V-shaped valleys. The threshold is presently decided upon by the user examining the typical grey-level values found at the perceived junction of trees crowns and their neighbouring shaded understory material. All pixels with grey-level values below this threshold are then set in the "shaded material" bitmap. The second step involves finding local minima in the remaining areas. Ideally, with the previous

threshold operation and the a priori masking of irrelevant areas, only moderate to densely forested areas would remain to be considered by this operation. In the geographical analogy, these points of local minima correspond to points where lakes collecting water from the whole watershed would exist. These points are then set in the "shaded material" bitmap (Figure 2b). The third step corresponds to the valley following per se. It consists in: (a) scanning the image, looking for the next pixel of "shaded material", which at this point should be a local minima or the boundary of a large shaded area delineated by the threshold; (b) looking around that pixel from a connected pixel flanked on both side by pixels with higher grey-levels (i.e., a V-shaped valley); (c) setting that pixel as "shaded material"; and (d) repeating step "b" and "c" until the valley thus followed connects with a pixel of "shaded material", then step "a" is invoked again. With the addition of allowances for flat bottom valleys that may have 2 or 3 pixels of similar values before a grey-level rise on each side, this algorithm essentially follows all of the shaded valleys in the image. Again, in our geographical analogy, it is akin to going up a valley (from a lake), finding a pass in the mountains, and going down the next valley to the next lake. Visually, this process appears to isolate most of the individual tree crowns visible in the areas of interest (Figure 2c). However, numerous potential crowns are actually tree clusters that could use further separation. In addition, it only knows about "shaded material" and does not know of the crowns (or clusters) as distinct entities. The rule-based delineation process that follows carries out these two mandates.

INDIVIDUAL TREE CROWN DELINEATION

The more precise delineation of the individual tree crowns and the "awareness" of the crowns as distinct entities for which specific information can be gathered (i.e., position, crown area, ...) is done by a rule-based delineation process. Generally speaking, it attempts to follow in a clockwise fashion a given crown outline by following in a rule-guided way the "shaded material" (extracted by the previous process) that is surrounding that crown. The process starts on the left side of a potential crown and the rules favour right-sided turns, dealing with increasingly complex exceptions from that general rule. When a crown (or tree cluster) has been delineated, the process starts over with another potential crown. Additionally, some of the higher level rules can split a cluster of "vegetation material" into more than one tree. The full process leads to a bitmap of individual tree crowns and, optionally, a database containing information on each tree crown.

More specifically, after having read the bitmap of "shaded material" (SM) and "non-forested" areas produced by the "valley following" isolation process, the delineation process starts by scanning the image (right and down) for a first minimal block (2x2 pixels) of "vegetation material" (VM - defined here as the converse of the bitmap just read in). Starting on the left side of this block, it tries to follow the SM up, or up and right, moving by one pixel. It will continue to move one pixel of SM at a time, favouring a move in its on-going direction or preferably, one pixel to the right of its on-going direction (level 1 rules). Sometimes the only possible move will be to the front-left of its on-going direction, for example, if a tree branch is protruding from the crown. This move will be acceptable under level 2 rules, assuming that level 1 rules have been checked previously. On other occasions the only path available while following the SM is 90 degrees counterclockwise to the on-going direction (e.g., larger branch sticking out). Such a move may be acceptable (level 3 rules), but only after having checked that a more favourable move cannot be executed by bridging a one-pixel-wide gap to some SM on the right or in front. Similarly, level 4 rules make possible turns that are 135 degrees counterclockwise, but only after substantial checking in the front-right direction for better moves that could be done by bridging gaps up to one meter wide. Finally, level 5 rules deal with possible moves implying a complete direction reversal from the on-going direction. Such situations typically represent a serious inlet into a crown (e.g., due to self-shading) or a serious indication that two or more crowns are present and should be separated. Again, a check is performed for SM up to a meter away from the end of the inlet to estimate whether a gap should be bridged. If it succeeds and the gap is bridged, it is possibly separating two distinct tree crowns. If this fails, the situation is considered as an irrelevant inlet within a single crown, and the inlet is actually erased before continuing the crown delineation. Higher level rules using less local perspectives and capable of decisions relative to tree cluster separation into crowns or re-merging of crown parts have not been implemented yet. A more detailed explanation of the existing rules can be found in Gougeon (1995). Typical results of the rule-based crown delineation programme are shown in Figure 2d.

Some of the factors used in the rules (e.g., one meter away) are not fixed and are actually dependent on a combination of the spatial resolution of the image and the sizes and types of trees being analysed. The spatial

resolution of the image is simply picked up from information stored in the image file header. The user can also orient the delineation process by using parameters such as: TREETYPE = regeneration, young, or mature. In fact, both the isolation and delineation processes are implemented within a suite of user-friendly C programs known as the ITC-suite (Gougeon *et al.*, 1998) requiring a minimum user interaction, keeping in-line with the goal of producing modern multi-resources forest inventories as automatically as possible. Finding the trees of a one metre resolution image covering an area of 5 km x 5 km on the ground (i.e., the kind of images expected from the next generation of satellite) can take as little as ten minutes (with a 200 MHz processor). It is expected that the full analysis of such an image, leading to individual tree species recognition and regrouping into forest stands or environmental strata, will not take an inordinate processing time (i.e., calculated in minutes). The amount of time for human interventions will be much more considerable, specially to train the classifier and verify the accuracy, and could take one or two days' worth of work at the computer.

STRENGTHS AND WEAKNESSES

Although delineation accuracy has not been completely tested yet (e.g., crown area accuracy), early results (Gougeon, 1995) indicated automatic tree counts from the delineation process to be within 7.7% of counts on the ground. When omission and commission errors (which tended to cancel each other) were taken into account, the tree counts were found to be 81% accurate. These tests have been done on a 31 cm/pixel MEIS image of mature coniferous plantation stands and compare favourably with human interpretations of aerial photos (1:2000) and of the MEIS image itself. However, the delineation approach is not always as efficient at properly separating individual tree crowns at coarser spatial resolutions. It tends to delineate more tree clusters (>20% reported above).

Preliminary tests of stem densities on 49 year old Douglas-fir plantations that had undergone thinning and fertilization experiments seen in a 60 cm/pixel *casi* image are not as encouraging. Tests using 27 plots ranging in densities from 650 to 1750 stems/ha (dominant and codominant trees) led to crown delineation densities of 525 to 775 stems/ha (average absolute error = 36.7%). Its theoretical limit, giving small trees that perfectly occupy the minimum 2x2 areas of "vegetation material" with valleys of shade of a minimum one pixel wide (even after smoothing), is of the order of 3000 stems/ha. However, this does not necessarily point to a tendency for the delineation process at 60 cm/pixel to saturate at a given upper limit of density (i.e., at 775 stems/ha). Indeed, when the stem densities found are shown as a relative stem density image (Figure 3), the situation corresponds well with the stem densities known to be present (Brix, 1993, Figure 1). Efforts to bring in other techniques, for example those based on finding local maxima (Gougeon & Moore, 1989; Pinz, 1991; Eldridge & Edwards, 1993; Dralle & Rudemo, 1996), to improve stem density estimations have not been very fruitful. It should be noted, however, that human assessment of that image is also problematic. There is a lack of visible separation of individual tree crowns which could be due to specific acquisition conditions. This is still the subject of investigations. Nevertheless, the test site was successfully used to derive volume estimations from "vegetation index" and "uniformity" parameters derived from the *casi* image (Magnussen & Boudewyn, 1998).

The main weakness of the delineation approach is directly related to its prime assumption: that the tree crowns in an image are usually separated by bands of shade. This means that, at present, this approach could be limited in its application to moderate to dense forest stands. It is also much more appropriate to the conical shape of softwood trees which typically leads to the creation of shade between the tree crowns. Fortunately, these are conditions that are often encountered in Canada's forests. In addition, when dealing with multispectral imagery, it is often possible to eliminate bright understory and open areas by various pre-processing techniques (see Gougeon & Leckie, 1988).

Another potential weakness, which could affect tree crown area estimation, is the use of a simple threshold to eliminate *a priori* the large shaded areas before the valley following *per se* actually starts. Figure 4 is an example of different results obtained with various thresholds. In addition, the illumination within these shaded areas is also affected throughout the image by the sun and view angles (and topography). This non-uniformity implies that for a given fixed threshold, crowns close to large shaded areas in certain parts of the image will tend to be larger, everything else being constant, than in other parts. The use of a BRDF-adaptable threshold (Yuan & Leckie, 1992; Leckie *et al.*, 1995) or a more sophisticated shade segmentation process (Gwinner & Schaale, 1997) may eliminate this problem.

Another problem arises when dealing with trees of substantially different sizes within the same image. With large tree crowns and/or high spatial resolution, and with certain tree crowns exhibiting pronounced radial branching patterns and self-shading properties (e.g., big Norway spruce), the delineation process has a tendency to penetrate the crowns and break them into numerous smaller crowns (Figure 5). It is possible to alleviate this tendency by using additional smoothing on the image. However, this is detrimental to the isolation and delineation of smaller trees on the same image. A self-adjusting smoothing filter, that locally applies more or less smoothing depending on the size of crowns it encountered (based on local variance or variograms), may be an appropriate solution.

The present rule-based system uses the assumption that crowns are relatively round objects. However, tree crowns that are seen significantly off nadir are anything but round. For coniferous trees, significantly off-nadir crowns can appear as triangles if front lit, or an inverted V, if backlit. Nevertheless, the present rules seem not to be encountering too many problems and the assumption of round objects seems not to be too detrimental to delineating objects of other shapes. In addition, with *casi* and MEIS images the off-nadir situations are not as dramatic as expressed above. These situations are more likely on large scale aerial photographs. In such cases, it is often possible, because of the high percentages of overlap between flight paths, to concentrate on image centres. More importantly, this problem is not going to be an issue with images from the next generation of satellite because of relatively narrow field of view.

A related possible weakness of the present delineation system is that of crown area accuracy. It may be assumed that even under ideal circumstances (at nadir, with trees immediately adjacent to each other), crown areas will be systematically underestimated by factors related to the spatial resolution of the image and the tree sizes themselves. For example, it is known that theoretically (assuming that the shaded side of crowns can be properly delineated from the shaded understory), tree crown areas will be deprived of at least half a pixel's width worth of area all around their circumference because the valleys of shade used to separate the crowns are at least one pixel wide. However, at this point in time, such a "systematic" underestimation is only a hypothesis and would, of course, only be valid close to nadir. With increasing off-nadir angles, the situation becomes a lot less predictable (see below). In on-going work (Leckie & Gougeon, 1988), where automatically delineated tree crowns are compared with their manually delineated (on screen) counterparts for species classification accuracy and crown delineation capability, encouraging preliminary results have been obtained with 36 cm MEIS data (Figure 6). On average, for a total of 357 manually delineated trees of 19 species in 24 field plots, crown areas, stem counts and canopy closure are in error by only 1.2%, 8.7% and 7.4%, respectively. However, on a one-on-one basis, only 58% of the automatic crowns intersect with the manual crowns by more than 50%. This difference between human and machine crown delineation needs to be investigated further, but currently, stand (or plot)-based estimations appear useful.

Even if good crown area estimations could be achieved (with a systematic error) at nadir, it would certainly break down with increasing view angles and the front-lit/back-lit situations mentioned previously. The tree crown localisation approaches based on a geometric modelling of the crowns (Pollock, 1994; Larsen, 1997) should have an advantage in this regard, as the model can be used to predict the real tree crown area from the apparent (viewed) tree crown. However, for satellite images, off-nadir viewing effects (significantly non-circular crown) are not a problem because of the satellite sensor's limited field of views. Similarly, complete aerial coverage of an area is typically done with substantial overlap between the image strips (or photos), allowing for the computer analysis to be concentrated on the centre sections of each strip (or photo). Nevertheless, geometric modelling of crowns could help in further separation of tree clusters. Thus, if partially integrated in the present system, it could serve these two purposes.

One advantage of a rather precise delineation process (specially at resolutions such as 30 cm/pixel) over the geometric modelling approach is that it makes possible an analysis of crown contour. Such information could be of use to infer (correlate with) actual tree crown structure. Other advantages, specially relative to methods that merely locate tree crowns (e.g., local maxima), are the possibilities of analysing the crown's textural and structural characteristics, as well as, some finer spectral characteristics. These may lead to better species recognition capabilities.

In some cases, specially at the lower spatial resolutions (60-100 cm/pixel), detailed ITC contour delineation may not be a concern. Similarly, apart from assessments of stem densities, sub-perfect crown separation may not be critical. It may be adequate to deal with a mixture of ITCs and tree clusters. Using the present delineation process with a 60 cm/pixel case image, species identification and regrouping into forest stands for species composition assessments provide very encouraging results (Gougeon, 1997; Gougeon *et al.*, 1998). In addition, compared to the model-based approaches mentioned above, this delineation approach is less computer intensive.

POSSIBLE FUTURE DEVELOPMENTS

Numerous possible improvements to the individual tree crown delineation process have been mentioned above. Some are already the subject of on-going research. The following list highlights some of the possible future developments:

- the automatic determination of a "large shaded area" threshold
- the development of a BRDF-adjustable threshold
- the elimination bright understory and open areas by various pre-processing techniques
- crown area accuracy testings (systematic underestimation / off-nadir effects)
- a shade segmentation process (by region growing) to replace the "large shaded area" threshold
- crown-size-adaptable smoothing (as preprocessing)
- access to the multispectral data to help the initial crown separation using multiple valley followings
- access to the multispectral data to help final crown separation by the rule-based system
- use of local maxima and/or moments to help decide on additional crown separations
- higher level rules using "less local" parameters to detect and further separate tree clusters
- higher level rules using "less local" parameters to detect and regroup crown segments into single crowns
- geometric modelling of crowns to help with tree cluster separation and off-nadir crown area estimations
- improvements of rules specifically geared to hardwood crown delineation
- non-erasure, in the valley following phase, of serious inlets into crowns because they could be used:
 - (a) for higher level separation decision later
 - (b) to produce valuable information on crown boundary structure for species recognition
- potential use of crown closure and stem density for biomass or merchantable volume estimations
- implications/importance of adding height information from LIDAR data
- addition of a digital terrain model to evaluate its importance

These are a few of the current short and long term research ideas being considered. Of course, new ones will surface as the work progresses; in particular, numerous issues will be raised as we try to operationalize this type of work.

CONCLUSION

A system based on following valleys of shade and contouring rules to automatically delineate individual tree crowns in remotely sensed aerial images or digitized aerial photographs of high spatial resolution (10-100 cm/pixel) was presented. Its present strengths and weaknesses were outlined. It works remarkably well at delineating individual tree crowns (ITC) at spatial resolutions around 30 cm/pixel (81% are 1:1 crowns), but its delineation capabilities have not been quantified yet at lower resolutions such as 50-100 cm/pixel. At these resolutions, tree clusters seem to be a bit more prevalent. Of course, numerous improvements are possible and some are already in the works.

The main benefit of this automatic ITC delineation system is that it makes possible a more complete system of ITC-based species recognition, followed by regroupings into automatically generated or existing forest stands, or environmental strata. Such an approach provides rather precise information about the content of stands and/or environmental strata, including species composition, stem density, canopy closure, gap assessments, to name but a few. This kind of information has not been previously available from digital remote sensing. Moreover, it should be possible in the near future to get it from satellite images. The kind of new

information this can potentially provide, such as gaps distribution for wildlife corridors or forest details for selective logging plans, is very compatible with a multi-resources management of our forest.

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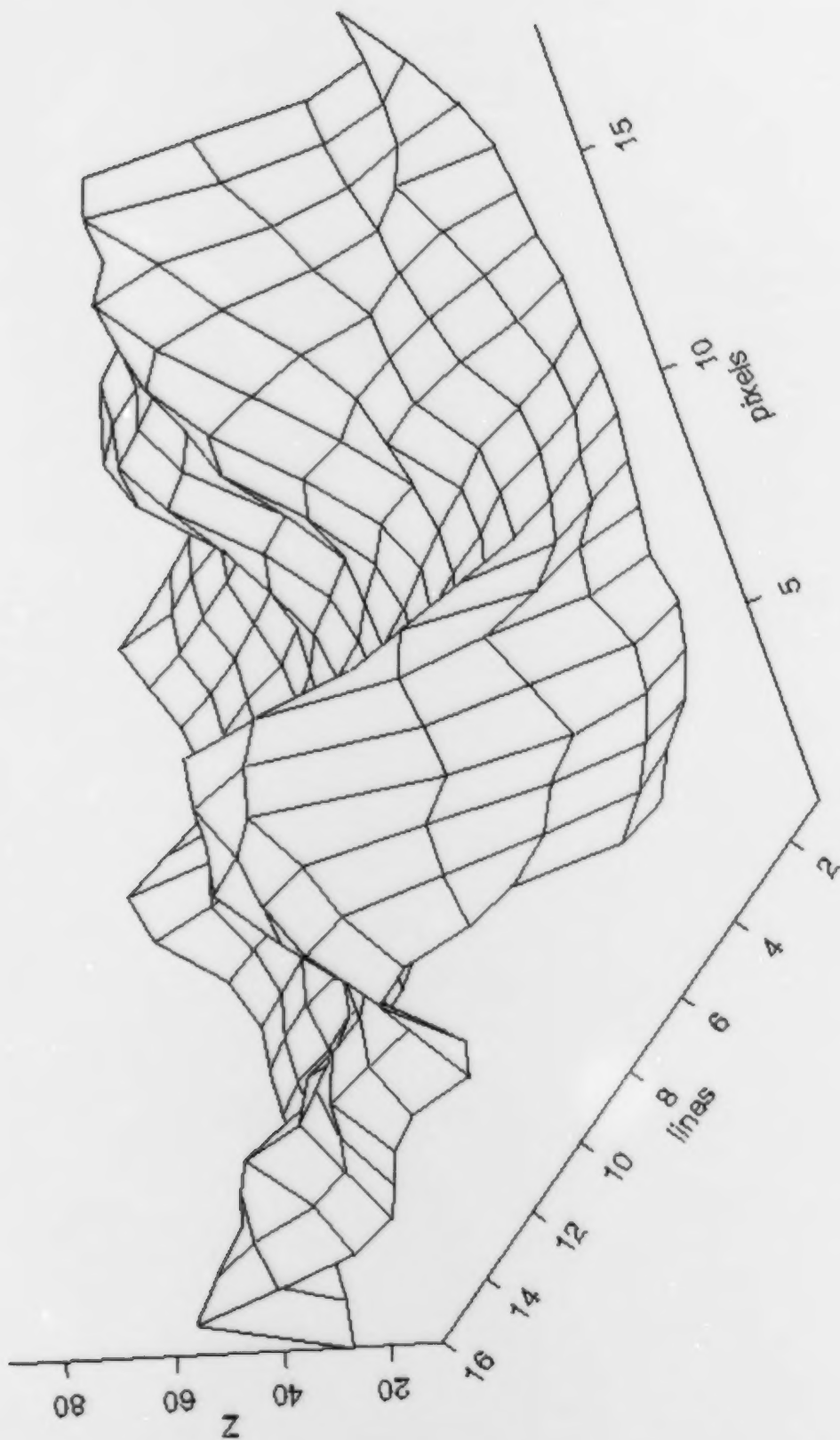


Figure 1. A three-dimensional view of a small section (16X20 pixels) of a MERS-II image showing the tree crowns brightness as mountains with valleys of shade separating them.

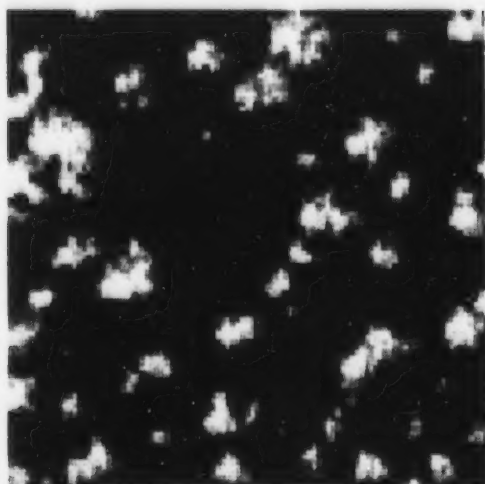


Figure 2a (left). Section (100x100) of the near infrared channel of a 31cm/pixel MEIS image (from Gougeon, 1995).

Figure 2b (right). Shaded areas and local minima of Fig. 2a (from Gougeon, 1995).

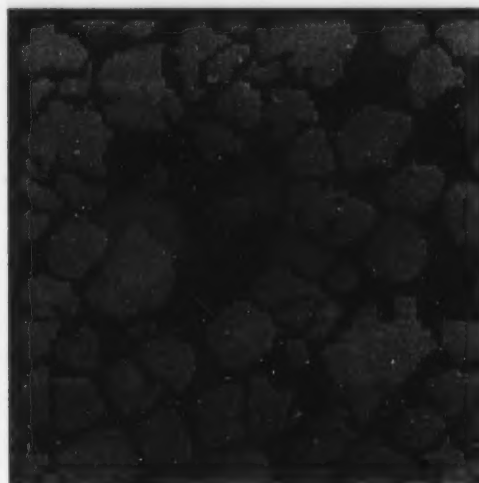


Figure 2c (left). Results after completion of the valley-following program (from Gougeon, 1995).

Figure 2d (right). Final results produced by the rule-based crown delineation program (from Gougeon, 1995).

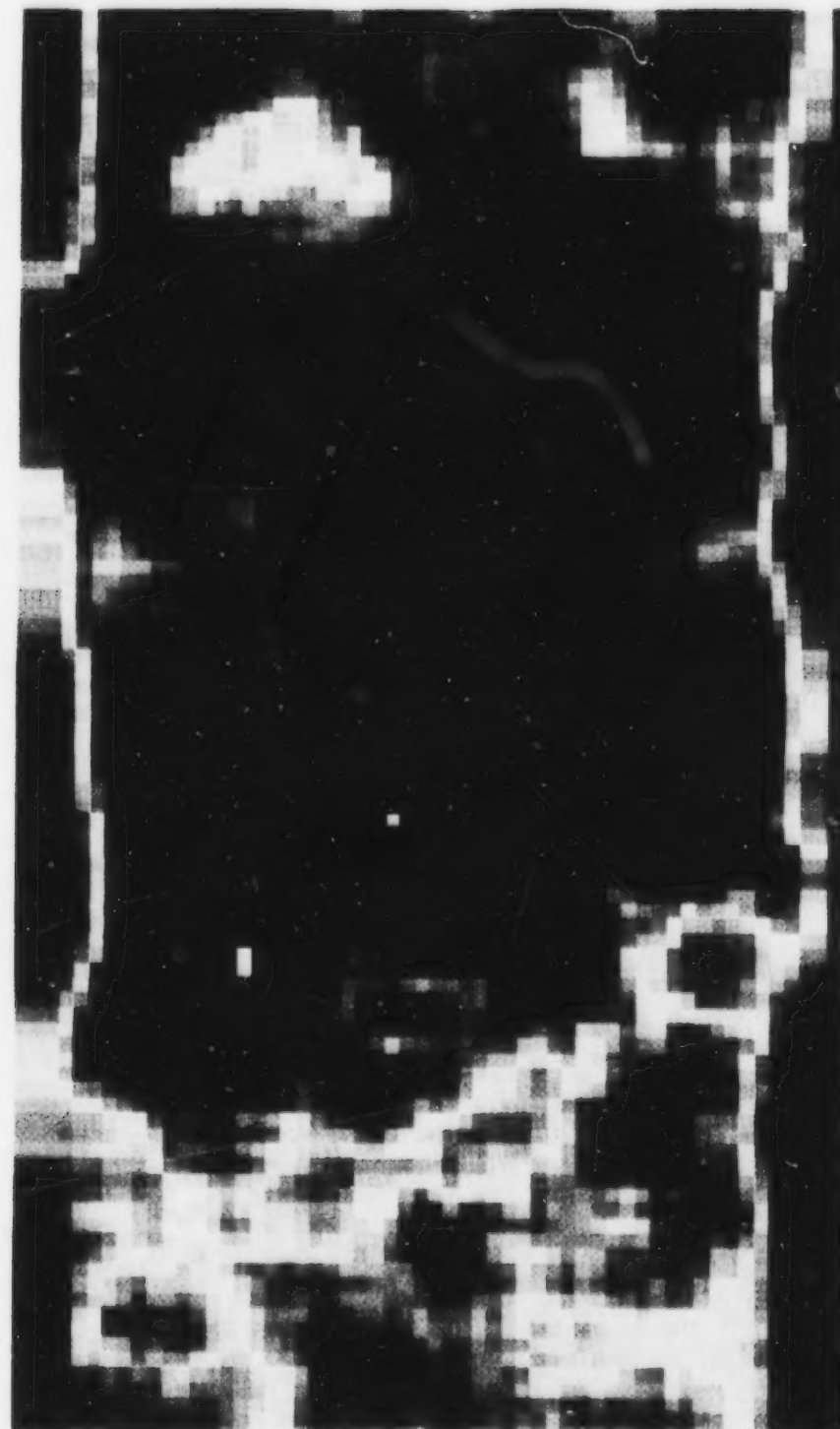


Figure 3. Stem density image derived from the automatically delineated individual tree crowns in a 60 cm/pixel aerial image of the Shawnigan test area, Vancouver Island, British Columbia. The "hotter" colours represent the denser areas.

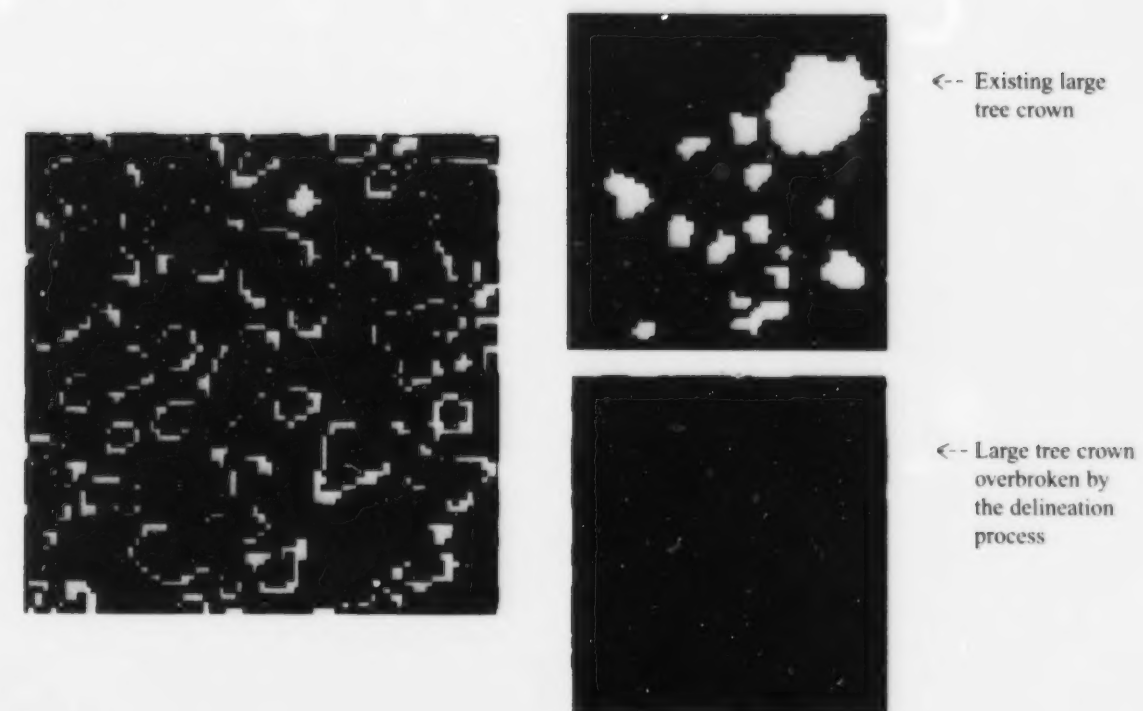


Figure 4 (left). Section of a 36cm/pixel MEIS image showing the differences in delineation results when different thresholds are used (blue = 23, yellow = 33, and red = 43).

Figure 5 (right). Example of a large tree crown being overbroken by the delineation process.

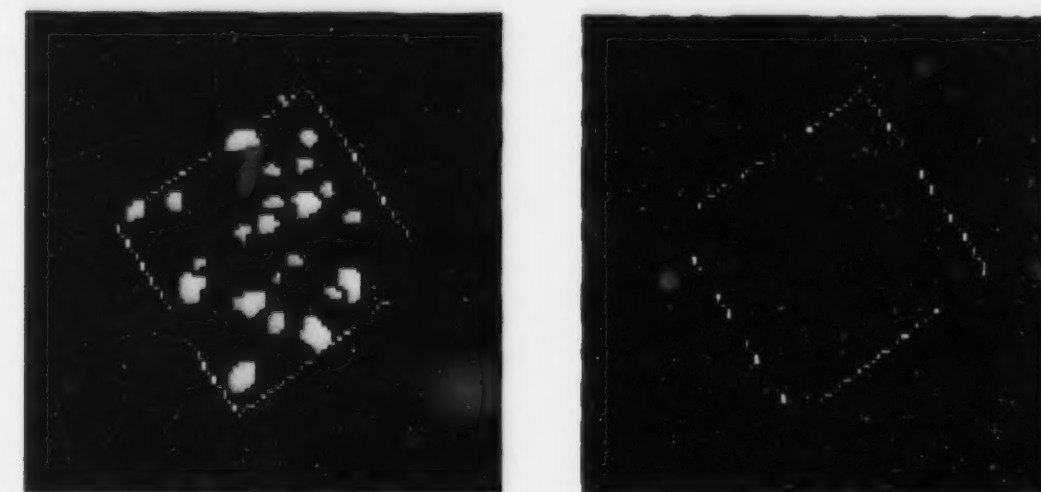


Figure 6a (left). Section (200x200) of a 36cm/pixel MEIS image showing a test plot and the manually delineated tree crowns within.

Figure 6b (right). The crowns automatically delineated by the ITC system for the same area of Fig. 3a.

INDIVIDUAL TREE RECOGNITION BASED ON A SYNTHETIC TREE CROWN IMAGE MODEL

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ABSTRACT

Individual tree crowns have been automatically recognized in monocular high-spatial resolution optical images of scenes containing boreal or cool temperate forests in a leaved state. The procedure is based on a model of the image formation process at the scale of an individual tree, user-generated training data, and the exploitation of a basic constraint on the spatial relationship of neighbouring trees. The procedure does not rely on the existence of explicit tree crown image region boundaries or on a large amount of contrast between the tree crown image region and the surrounding image region.

The procedure has been tested on image data acquired with the MEIS II and CASI sensors for scenes in Ontario and Alberta. The ground-projected IFOV that the data were acquired with is 36cm (MEIS II) and 60cm (CASI).

The tests results show that the procedure is largely able to accommodate the variation represented by the scenes, but that significant errors are related to irregularities in tree crown form and irradiance that are caused by tight vertical and horizontal spacing of the crowns (relative to the spatial resolution of the image data), and to the inability to resolve trees with crown diameters of approximately 1m or less.

RÉSUMÉ

IDENTIFICATION D'ARBRES BASÉE SUR UN MODÈLE DE SYNTHÈSE D'IMAGES DE HOUPPIERS

Les houppiers des arbres ont fait l'objet de reconnaissance automatique dans des images optiques à haute résolution spatiale représentant des scènes de la forêt boréale ou tempérée fraîche, en feuilles. La procédure est basée sur un modèle du processus de formation d'images à l'échelle de l'arbre individuel, sur des données d'entraînement produites par l'opérateur et sur l'exploitation d'une contrainte de base sur la relation spatiale des arbres avoisinants.

La procédure a été testée sur des données d'images acquises avec les capteurs MEIS II et CASI pour des scènes en Ontario et en Alberta. Le champ de vision instantané au sol pour la collecte des données est de 30 cm (MEIS II) et de 60 cm (CASI).

Les résultats des tests indiquent que la procédure permet très bien de tenir compte des variations contenues dans les scènes, mais que des erreurs importantes sont associées aux irrégularités dans la forme des houppiers et dans l'éclairement énergétique, lesquels sont causées par un espacement vertical horizontal serré des houppiers, et à l'incapacité d'identifier des arbres dont le diamètre du houppier est d'environ un mètre ou moins.

INTRODUCTION

The overall objective of this work was to develop a highly-automated procedure for the recognition of trees in monocular high spatial resolution optical images of scenes containing boreal or cool temperate forests in a leaved state. This work is intended to contribute to the development of a system for automatically extracting information relevant to forest type mapping from such images. The procedure is based on a model of the image formation process at the scale of an individual tree. This model provides a means of applying specific scene and image formation knowledge to the recognition task. Natural variation of tree crown size, shape, and composition is considered, as well as tree-image variation (including the effect of height displacement) that is a function of image geometry. The procedure also uses user-generated training data and exploits a basic constraint on the spatial relationship of neighbouring trees.

The procedure associates instances of a three-dimensional shape description with locations in a scene image such that the descriptions estimate the visible scene extent of tree crowns that existed at the corresponding scene locations when the image was acquired (Figure 1). This provides an estimate of the average horizontal diameter of the vertical projection of individual recognized tree crowns, and a basis for species classification.

Specific objectives of this work were that (1) the procedure not be limited in applicability to stands consisting of uncrowded trees all of similar shape and occupying a narrow size range, and (2) that the full extent of an image could be processed (in contrast to processing only the part of an image that corresponds to a near-nadir view of the scene).

The training and recognition procedures are outlined in Section 2, tests of the recognition procedure are described in Section 3, and Section 4 is the conclusion.

OUTLINE OF THE TRAINING AND RECOGNITION PROCEDURES

The processing strategy that was adopted in this work is based on the use of a synthetic image model of tree crowns. This model is defined for only a single image channel and only up to, but not including, the application of a uniform gain and offset. This image model facilitates a manual training set selection procedure. Further constraints that are related to absolute apparent radiance in one or more wavelength regions and to the gains and offsets that were applied independently to one or more image channels are derived from the training set. The recognition procedure uses the image model that has been extended with example-based knowledge derived from the training set.

The image model is defined by both geometric and radiometric aspects. The geometric aspects consist of the crown envelope shape and the sensing geometry. The radiometric aspects consist of the scene irradiance, the interaction of the scene irradiance and the tree crown, and the sensor irradiance. The synthetic component of the image model includes a parameterized three-dimensional description of general crown envelope size and shape. Each association of a model instance and an image location is called a *recognition instance*. The projection of the spatial extents of the estimated crown envelopes onto the image provides image-space localization of tree crown image extent. Crown diameter estimates are derived from the model instance parameter values.

Figure 2 illustrates an instance of the synthetic image model. The crown apex has an off-centre location because of modelled height displacement. The implementation includes a representation of the overall and direct irradiance image extents, which are used in computing tree crown image features in the training and recognition procedures.

The overall strategy is to compute a set of initial recognition instances that satisfy inexpensively applied constraints derived from the image formation knowledge, but that may also contain a large proportion of false instances, and then to filter the recognition instances in further processing steps that involve constraints that are applied at greater expense per recognition instance. The strategy is described in further detail below and illustrated in Figure 3.

The training set selection procedure and the recognition procedure share the same initial step. In this initial step the image extent and the parameter space of the synthetic component of the image model are searched for locations where a measure of the strength of the match between the synthetic model instance and the local pattern of image values is at a local maximum and is no lower than a liberally-specified threshold. These matches constitute the initial recognition instances. The search region of the model parameter space is defined by the user-specified model parameter value intervals. In the training set selection procedure, image regions that correspond to a sample of the full range of crown and stand types in the overall scene are manually defined. Examples of correct and incorrect recognition instances are then manually selected from the initial recognition instances within these image regions, and features involving the image values within the corresponding tree crown image regions are evaluated for these examples.

In the training procedure the user is not required to manually delineate or window individual tree crown image regions. The avoidance of such a painstaking task is significant with respect to speed and convenience (and also to the continued sanity of the user).

The example-based component of the image model is applied in the second step of the recognition procedure. For each of the initial recognition instances, the features are evaluated and the probability that the instance is correct (the *correct recognition probability*) is estimated on the basis of the distribution of the elements of training set in the feature space. Initial recognition instances with a correct recognition probability value under 0.5 are rejected.

The results of the second step of the recognition procedure (the intermediate recognition instances) are expected to sometimes contain conflicting interpretations of the same image region (i.e., one large crown image versus multiple small crown images), since each intermediate recognition instance is established independently of any other. The goal of the third and final step of the recognition procedure is to resolve conflicts due to physically implausible spatial relationships among the intermediate recognition instances while retaining a good overall interpretation of parts of the image that portray forest cover. The physical constraint that within forest stands the volume of the crown envelope intersections is generally less than the remaining crown envelope volume is applied in this step. This is possible because each recognition instance is associated with a crown envelope boundary defined in both the scene-space and the image-space.

Further details on the training and recognition procedures are available in Pollock (1996).

TESTS OF THE PROCEDURE

Two tests of the training and recognition procedures have been conducted. The first test was conducted on images of scenes within the research forest of the Petawawa National Forestry Institute (PNFI) near Chalk River, Ontario, Canada (Section 3.1). The second test was conducted on images of scenes within the Athabasca 24 compartment of the Weldwood of Canada, Ltd. forest management area near Hinton, Alberta, Canada (Section 3.2).

PNFI RESEARCH FOREST TEST

The PNFI images were acquired during the morning of 16 August 1988. The scenes contain mixed forest and represent many different stand types, including mixed hardwood and softwood stands, and a wide range of individual tree size. The images were acquired in multiple wavelength regions with the second generation of the multi-detector electro-optical imaging scanner (MEIS-II), a pushbroom scanner (McColl et. al. 1983). The images have a 36cm ground projected pixel dimension. Figure 4 displays some of the PNFI image data, scene variation, and samples of the results that were produced by the recognition procedure. In many places the boundaries between tree crown images are unclear or only implicit and there is not a large amount of contrast between the tree crowns and their background. Nevertheless, the figure shows that the procedure is largely able to accommodate the variation represented by the scenes.

During the periods of May to October 1989 and May to August 1990 various attributes (including crown diameter) of a sample of 587 overstory trees that were distributed among twenty-four 20-by-20 metre square sample plots in the scene were evaluated in the field by PNFI personnel. PNFI personnel also manually estimated the crown apex image location for 548 of the sample trees (these locations were confirmed through field visits with hardcopies of the image data), the image extents of the crowns of 539 of the sample trees, and the image location of each corner of each sample plot. The reference data collection procedure is described in further detail in Cloney et al. (1994). These data were used to assess the accuracy of the results produced by the recognition procedure. A summary of the results is given below. Further information on the accuracy assessment procedure and the results are presented in Pollock (1996).

The errors in automatic recognition results were mostly omission errors. Automatic recognition errors were evidently caused by non-ideal crown irradiation, irregular crown form (especially for some hardwood trees), partial occlusion of tree crowns due to height displacement, faulty interpretation of tight clusters of tree crowns as relatively large tree crowns, and faulty integration of the results for adjacent processing windows. The errors in the automatic and manual image-based crown diameter estimates were comparable. Both sets of estimates tended to be low relative to ground measurements, probably because of the intersection of tree crowns and the failure to resolve branches at the outer crown extent that are visible from the ground.

A more detailed summary of the results assessments and analyses follows:

Recognition results:

- The automatic recognition results were assessed twice, according to two different sets of rules. The liberal assessment, which de-emphasizes correct image-space localization, was intended to produce error counts that can be compared to the manual recognition results. The conservative assessment placed more emphasis on correct image-space localization.
- The numbers of commission errors in the manual and the liberally assessed automatic recognition results are close: respectively 10% and 11% of the 340 sample trees. However, the number of liberally assessed automatic recognition omission errors (38%) is 2.8 times the number of manual recognition omission errors (14%). The numbers of conservatively assessed errors are only slightly greater than the numbers of liberally assessed errors.
- Inspection of the results for select test sample plots revealed evidence of the following:
 - some tree crowns were not recognized because direct solar irradiation that would otherwise have reached them was intercepted by neighbouring trees,
 - some recognition errors occurred because of the requirement for a large amount of overlap in the interpreted crown boundaries in cases where height displacement caused tree crowns to partially occlude each other,
 - some large hardwood trees were unrecognized because they had an irregular crown form that was caused by growing under competition, and some because they had a basic crown architecture that does not correspond well to the simplifying assumptions of the tree crown image model,
 - tight clusters of tree crowns were sometimes recognized as the directly irradiated portion of a single relatively large tree crown when the cluster image was juxtaposed with a dark image region along the image projection of the direct solar irradiation direction,
 - some errors were produced by faulty integration of the results for adjacent processing windows.

- Most commission errors were due to the recognition of portions of tree crown images as separate relatively small tree crowns.
- Pairs of opposing properties that correspond to pairs of disjoint test population subsets were defined, and for each pair the null hypothesis that equal proportions of those subsets would be automatically recognized (H_0) was tested using the test sample tree recognition results.
- The results of the significance tests provide strong evidence that H_0 can be rejected for crowding variation between low and medium levels and for dominance variation. There is also strong evidence that H_0 can be rejected for species class variation (softwood vs. hardwood) when consideration is limited to trees with average or greater than average crown diameter but not when consideration is limited to trees with smaller than average crown diameter.
- The results of the significance test provide little or no evidence that H_0 can be rejected for absolute column offset variation (even when consideration is limited to trees under medium or high crowding), for crowding variation between medium and high levels, or for crown diameter class variation (diameter greater than or equal to average vs. diameter less than average).

Crown diameter estimation results:

- Automatic and manual image-based crown diameter estimates were compared to field measurements of crown diameter on the basis of two different sets of crown diameter classes: the full-resolution set (with 1.0 to 1.4m wide class intervals) and the half-resolution set (with 2.2 to 2.3m wide class intervals).
- Both the automatic and manual image-derived crown diameter estimates tended to be low for both sets of classes.
- The overall agreement of the automatic image-based crown diameter classification with the field measurement-based crown diameter classification is 0.434 for the full-resolution classes and 0.707 for the half-resolution classes.
- For each error matrix, the Tau coefficient permits the rejection of the hypothesis that the image-based crown diameter classification results only represent chance agreement and do not permit the rejection of the hypothesis that the automatic and manual crown diameter image-based classifications are equally accurate.

ATHABASCAN 24 COMPARTMENT TEST

The Athabasca 24 images were acquired during the early to mid afternoon on 24 July 1996. The scenes contain mostly coniferous forest and some aspen stands and have a less varied species composition than the PNFI scenes. Nevertheless, the Athabasca 24 scenes represent a wide range of tree size. The images were acquired in multiple wavelength regions with the compact airborne spectrographic imager (CASI) (Babey and Anger 1989). These images were acquired with a 60cm ground projected IFOV. During the georectification step, the images were nearest-neighbour resampled by the data provider such that the output (the images that the recognition procedure was run on) have a 50cm ground-projected pixel dimension. Figure 5 displays some of the Athabasca 24 image data, scene variation, and samples of the results that were produced by the recognition procedure. The figure shows that the procedure is largely able to accommodate the variation represented by the scenes. This figure also shows very clearly that the procedure recognizes entire tree crowns, in contrast to recognizing only the directly irradiated portion of each crown.

Early in the examination of the image data and the recognition results, it was concluded that the spatial resolution of the image data and aliasing caused by the nearest-neighbour resampling were very likely significant hinderances to both manual and automatic tree crown recognition. Field visits confirmed that many relatively small trees of merchantable size could not be manually resolved in the image data. Because of this,

only a superficial (relative to the PNFI test) assessment of the results was conducted. Funds that were to be spent on more intensive fieldwork in Athabasca 24 have been diverted to the assessment of the results that will be obtained in a future project involving a site in Northern Alberta. For this project, image data will be acquired with an approximately 20cm ground-projected IFOV in the summer of 1998. This will be done with a multispectral digital frame camera system.

A comparison of the recognition results within six 1 hectare Athabasca 24 scene regions with on-foot field observations revealed that the following were common errors:

- Trees with a crown diameter less than 1m were often missed, even when they grew in uncrowded conditions.
- Tight groups of small trees (i.e., crown diameter of approximately 1m or less) were often automatically recognized as a single crown.
- Where crowns are relatively close together, shorter and smaller crowns were often missed.
- Forked trees were usually recognized as single crowns.
- Members of tight groups of aspen have highly irregular crowns and were often either missed altogether (i.e., interpreted as ground vegetation), or were interpreted as a group of relatively few trees.

These errors usually could not be recognized through manual interpretation of the image data alone.

The field observations revealed that near-infrared/red/green false-colour composites of the Athabasca 24 data often contain clear colour-distinctions between different coniferous species (lodgepole pine, white spruce, tamarack) and obvious colour distinctions between coniferous species and aspen, at least where individual tree crowns are easily recognized. An automatic supervised classification of tree crown image regions based on multispectral image values within the direct irradiation portions of these regions (cf., Figure 2) yielded results that were consistent with manual interpretation results.

Much of the recognition procedure was re-implemented between the PNFI and Athabasca 24 tests. This increased the execution speed of the procedure significantly. Image data for 1,500 hectares (0.5m pixels) were processed in under 5 hours on a computer with a single 200MHz Pentium Pro processor.

CONCLUSION

The individual tree recognition procedure described in this paper permits readily acquired knowledge of the sensing system, the sensing situation, and physical properties of individual tree crowns in the scene to be used to constrain the task of collecting example-based data on tree crown images, and to constrain the recognition task. The procedure does not rely on the existence of explicit tree crown image region boundaries or on a large amount of contrast between the tree crown image region and the surrounding image region.

The automatic recognition results that were obtained with image data acquired using a 36cm IFOV had significantly more omission errors than manual recognition results obtained with the same image data.

Tests of the recognition procedure strongly suggest that improved spatial resolution (e.g., that of digital image data acquired with a 20cm IFOV) is required in order for the procedure to produce tree recognition results that would be generally accepted for use in forestry operations. The tests also indicate that greater accommodation of irregular tree crown form is required. These concerns are addressed in improvements to the procedure that are currently underway.

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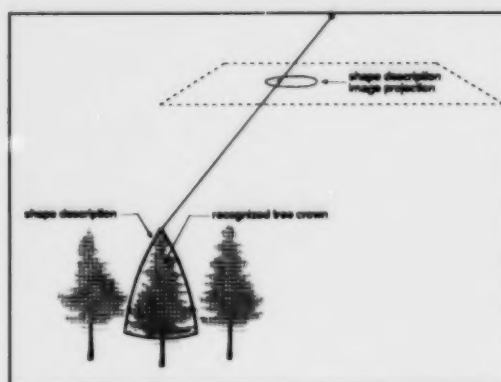


Figure 1. Tree crown recognition scenario.

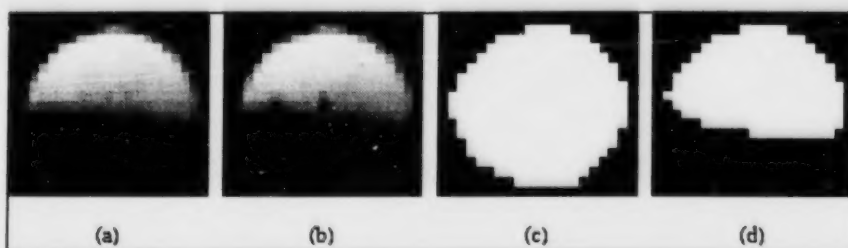


Figure 2. Synthetic tree crown image model instance (a), superimposed apex and extent centroid locations (b), extent locations (c), and direct irradiation locations (d).

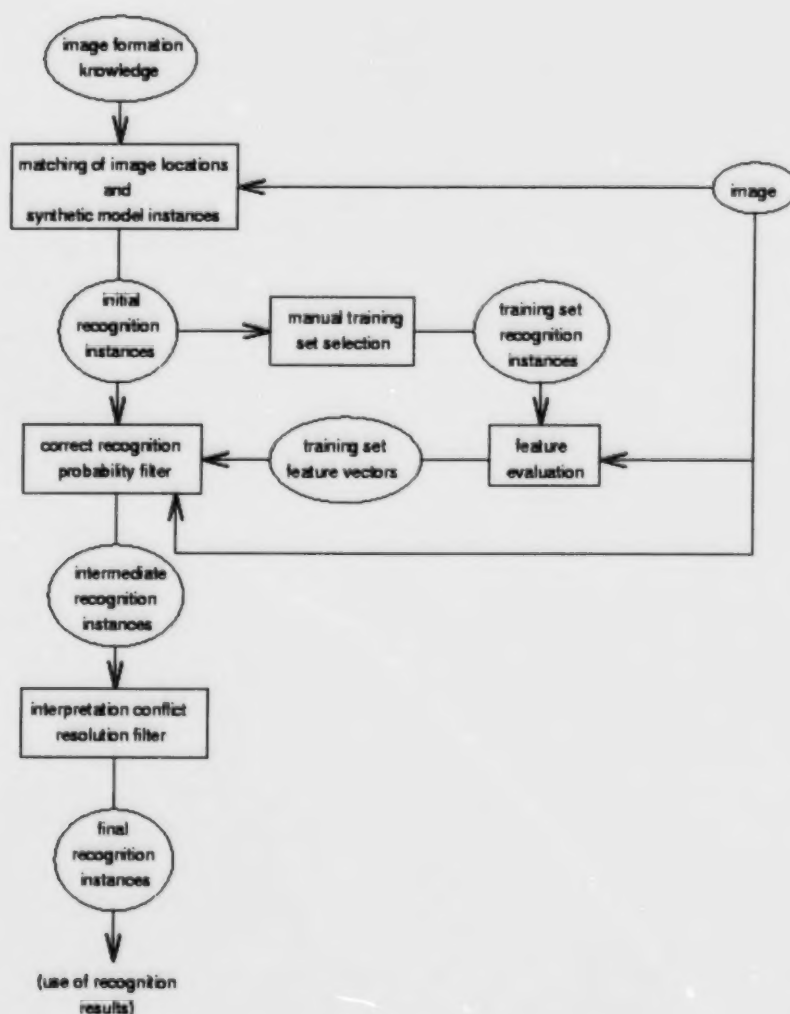


Figure 3. Processing strategy (ellipses label data, boxes label operations).

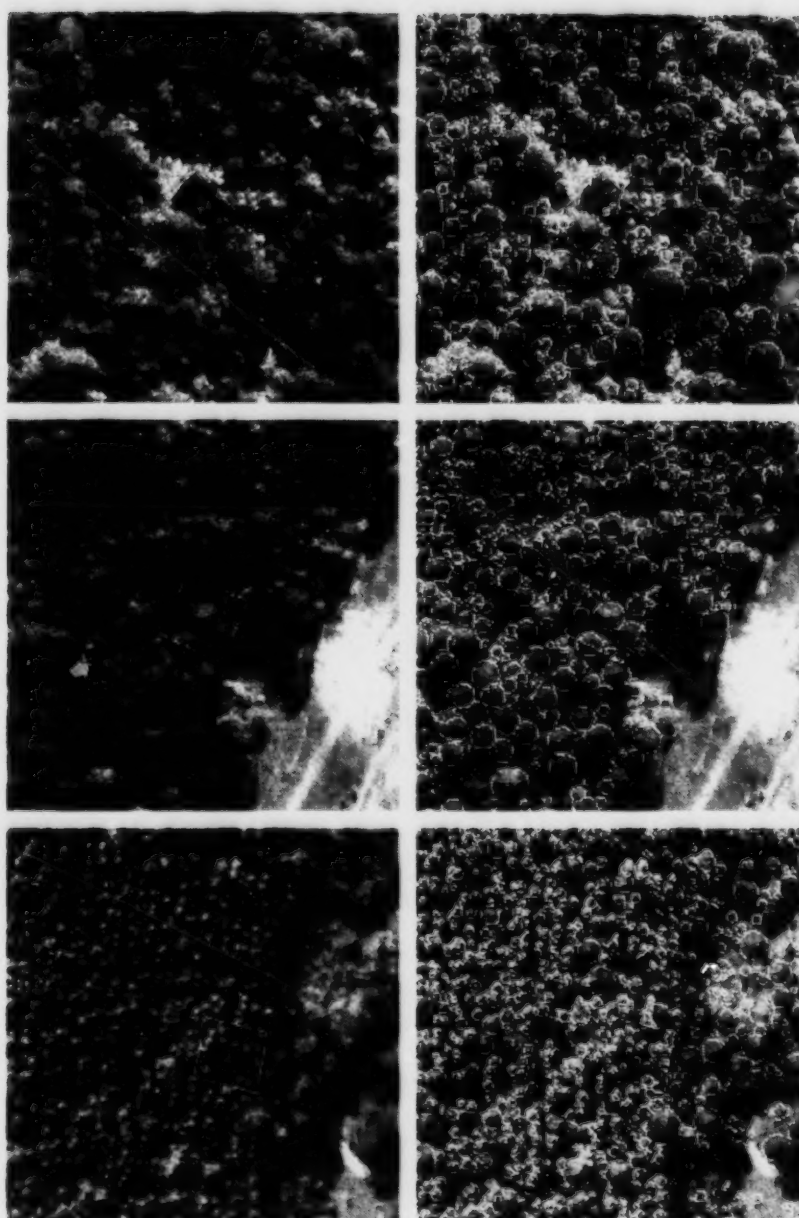


Figure 4. Subimages from the image data and automatic individual tree crown recognition results for 1 hectare PNFI subscenes. The subimages were extracted from the visible green wavelength channel of the test image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column. The boundary of a 20-by-20 metre ground sample plot is superimposed in white on all of the subimages.

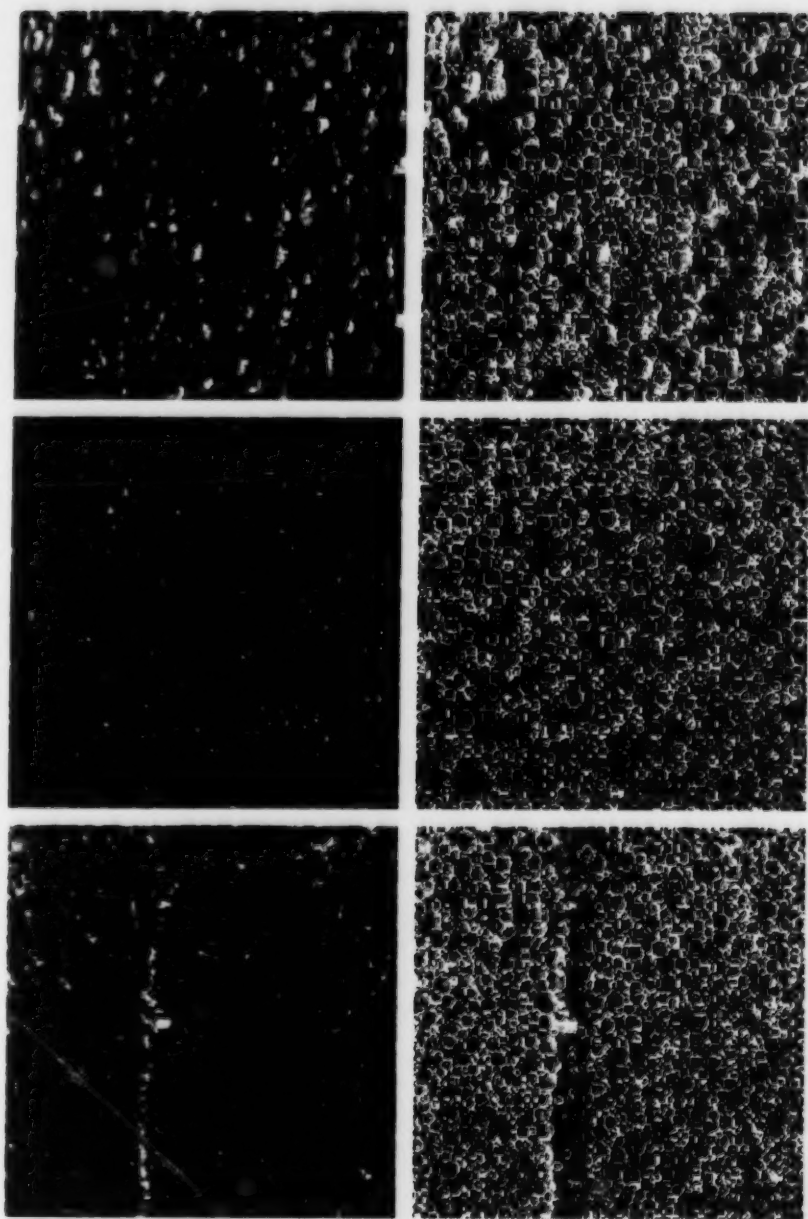


Figure 5. Subimages from the image data and automatic individual tree crown recognition results for 1 hectare Athabasca 24 subscenes. The subimages were extracted from the visible green wavelength channel of the image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column.

SPATIAL TREE PATTERN ANALYSIS FROM MAXIMA OF SMOOTHED AERIAL PHOTOGRAPHS

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ABSTRACT

An aerial photograph of a forest is digitized and smoothed, e.g. by a spherically symmetric kernel at a suitably chosen bandwidth or by matching of templates derived from a light reflection model. The maxima of the smoothed image yields estimates of individual tree positions and thus allows statistical analysis of the spatial neighbour patterns, which are important for predicting future growth and timber quality of the trees.

Theoretically, the statistical problem is estimation of one marked point process from observation of another such process. In our application the process to be estimated is the true tree position process with marks consisting of stem height, stem diameter and crown shape. The observed point process corresponds to local maxima of the smoothed image with marks determined by the local properties of the image close to these maxima.

RÉSUMÉ

ANALYSE SPATIALE DE FORMES D'ARBRES À PARTIR DE MAXIMUMS DANS DES PHOTOGRAPHIES AÉRIENNES FILTRÉES

Photographie aérienne d'une forêt, numérisée et filtrée à partir d'un logiciel d'évaluation à symétrie sphérique dans une bande de fréquences appropriée ou en couplant des gabarits dérivés d'un modèle de réflexion de lumière. Le maximum de l'image lissée permet d'établir des estimations d'emplacements d'arbres et, par conséquent, de procéder à l'analyse statistique des diagrammes d'avoisinage spatial, lesquels sont importants pour prédire la croissance future des arbres et la qualité des grumes.

En théorie, le problème statistique réside dans l'estimation d'un processus ponctuel avec repères découlant de l'observation d'un autre processus du genre. Dans la présente application, il s'agit d'estimer le processus visant à établir l'emplacement réel d'un arbre avec des repères comme la hauteur et le diamètre de la tige ainsi que la forme du houppier. Le processus ponctuel observé correspond au maximum local de l'image filtrée avec des repères qui sont déterminés par les propriétés locales de l'image, à proximité de ces maximums.

INTRODUCTION

The theory of point processes and the closely related theory of marked point processes have been vigorously developed during the last two decades, and one of the main sources of inspiration has been spatial

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problems from biology and geography. Highly useful expositions of the theory with many applications have recently been given by Cressie (1991), Stoyan and Stoyan (1994) and Stoyan, Kendall and Mecke (1995).

In this paper we will concentrate on the analysis of spatial patterns where the points represent trees in a stand. However, before treating our main example, two other examples of spatial point patterns will be discussed briefly.

In the first example weed density is estimated by use of a colour photo, taken from above, showing crop, weed plants and soil. The underlying point process consists of plant positions and the mark associated with a point consists of the species of the corresponding plant and the form of its green parts. The observed marked point process consists of green segments obtained by an automatic image processing technique. The problem here is that each green part may consist of exactly one weed plant, but it may also consist of several weed plants and parts of crop or crop alone. The crucial problem in our weed density estimation problem is then to estimate for each green segment the number of weed plants as accurately as possible.

In our second example a sequence of weather radar images are observed. Each image is approximated by a mixture of Gaussian distributions with individually varying covariance parameters. Each component in the mixture is supposed to correspond to a rain cell, and from the sequence of images rain cells may be tracked.

One important source of examples of marked point processes is forestry as shown by Matérn (1986), Diggle (1983), Tomppo (1986), Penttinen, Stoyan and Henttonen (1992), Rathbun and Cressie (1994) and Särkkä (1995). Here the points typically are positions of trees, while marks consist of associated variables such as tree height, diameter and crown width. Our main example of spatial point patterns belongs to this category. We have an aerial photograph which is digitized. Potential trees are either obtained as maxima after smoothing with a Gaussian kernel, or from maxima of the correlation function obtained by translating a model tree template over the observed image. This gives an observed point process, which is used to estimate properties of the underlying true point process of tree positions.

Let us introduce some notation. We let $\mathbf{X} = (X_i, M_i^X)_{i \in I}$ denote the true marked point process with point positions $X_i \in \mathbb{R}^2$, where $\mathbb{R}^2$ denotes two-dimensional Euclidean space, and the marks M_i^X take values in a suitable space of marks. Similarly $\mathbf{Y} = (Y_j, M_j^Y)_{j \in J}$, where $Y_j \in \mathbb{R}^2$, denotes the observed marked point process with a parallel notation. The spaces of marks for the true and for the observed marked point processes are often different.

Some basic problems are then:

- 1) For test data with observations of both $\mathbf{X}$ and $\mathbf{Y}$: to estimate the joint distribution of $(\mathbf{X}, \mathbf{Y})$, in particular, the conditional distribution of $\mathbf{Y}$ given $\mathbf{X}$.
- 2) For later applications with observations only $\mathbf{Y}$: to estimate $\mathbf{X}$ given $\mathbf{Y}$.

WEED DENSITY ASSESSMENT AT AN EARLY STAGE

Andreasen et al. (1997) study a set of 100 images obtained by digitizing colour photographs from 5 barley fields. Each photograph is taken from a height of 70 cm and covers a ground area of $14.7 \times 22 \text{ cm}^2$. In these images the number of weed plants per square meter ranges from about 10 to about 1140, which is considerably more than could be expected from pure Poisson variation.

A semi-automatic and an automatic method for estimating the weed density are suggested. The methods are based on marked point process models and are designed to correct for overlapping plants and for border effects by use of techniques developed in stereology as discussed by Miles (1974).

The semi-automatic method gives quite satisfactory results, but it is time-consuming, and it can, of course, not be used in applications such as automatic adaptive dosage of herbicides. In the automatic method the crucial problem turns out to be estimation of the number of weed plants associated with each segment identified by an automatic segmentation method. These segments are the marks of the observed

marked point process and in Andreassen et al. (1997) only two simple features of each mark are exploited: the size of the segment and whether the segment cuts the image border or not. It turns out that the number of weed plants associated with a segment increases with the size of the segment. Furthermore, border-cutting segments tend to contain on the average fewer weed plants than segments that do not cut the border, and this tendency is particularly conspicuous for small and average-sized segments. The resulting estimator for the number N of weed plants in a image takes the form

$$\hat{N} = \hat{\beta}_1 \sum_{S \in I} R_1(|S|) + \hat{\beta}_2 \sum_{S \in B} R_2(|S|),$$

where B is the set of border-cutting segments in the image, I is the set of inner (not border-cutting) segments, $|S|$ denotes the area of the segment S and R_1 and R_2 are logistic-type response functions for the inner and border-cutting segments, respectively.

The two features mentioned above have both highly significant influences on the weed density. It is clear from the discussion in Andreassen et al. (1997) that, although the present version of the automatic method is not sufficiently accurate, an extended analysis, where also other features of the segments are included, has a potential for considerably improving the method. Here features related to properties of the segment contours seem particularly promising. We note further that the general methodology of basing the inference on the observed marked point process with marks consisting of segments of green parts should still be valid with such an extended set of features.

Some further aspects of the weed density estimation problem, particularly from an image analysis point of view are discussed by Rudemo et al. (1995).

PRECIPITATION FORECASTS FROM WEATHER RADAR IMAGES

Larsen (1994, 1995) studies sequences of weather radar images observed with 10 minutes intervals. The grey level images in a series are viewed as regression functions in two dimensions and they are approximated by mixtures of Gaussian distributions with individually varying covariance parameters, but with restrictions on the variations from one image to the subsequent one. A Kalman filter model is suggested in Larsen (1995), and it is shown to estimate the motion of the rain cells in a low pressure area satisfactorily. Even the motion of the low pressure center can be estimated indirectly from the motion of the rain cells.

STEM NUMBER ESTIMATION AND INDIVIDUAL TREE POSITIONING FROM AERIAL PHOTOGRAPHS

The number of stems in a forest plot is estimated by Dralle and Rudemo (1996) from a panchromatic aerial photograph by smoothing the digitized image by a symmetric two-dimensional Gaussian kernel with a suitably chosen bandwidth. The points of the underlying true marked point process are the tree positions, and as the mark corresponding to a tree we may choose the triple consisting of the diameter at breast height, the height of the tree and the shape of its crown. The points of the observed point process are the local maxima (above a suitable threshold) of the smoothed image, and as the mark corresponding to a local maximum we could choose the height of the local maximum or some suitable region surrounding the location of the local maximum.

A method for choosing the optimal bandwidth of the smoothing kernel is suggested as the bandwidth corresponding to the crossing of an "internal" and an "external" curve. The internal curve for a subplot of the plot considered is computed by smoothing the image at a series of bandwidths and by plotting the logarithm of the stem density versus the logarithm of the bandwidth.

Typically the internal curve is a decreasing curve. In fact, one can show that in one dimension this holds generally under proper conditions for a Gaussian kernel (Silverman, 1981). However, in two and higher dimensions this is no longer true as may be shown by simple counter-examples (Lindeberg, 1994).

The external curve has to be supplied from a set of images corresponding to different stem densities. In Dralle and Rudemo (1996) data from a set of subplots with varying thinning treatments in a thinning experiment are available, and it is shown that a linear external curve performs well. We note, in passing, that thinning experiments are ideal for this type of study: the crucial quantity, namely, the tree density varies considerably while other parameters such as the genetic origin of the trees, tree age and lighting conditions during the aerial photography are held constant.

Estimation of tree positions by use of kernel smoothing was studied in Dralle and Rudemo (1997). The method was found to perform satisfactorily for trees reasonably close to the nadir point (Dralle, 1997).

An alternative method was studied in Larsen and Rudemo (1997) and Larsen (1997), where an optical tree crown model introduced in Pollock (1994a, 1994b, 1996) was extended. The method gives a template for an individual tree adapted to the geometry at image acquisition. Tree top positions are estimated as local maxima of the correlation function for the successively transposed template over the whole image. The method was found to improve the kernel smoothing method for off-nadir viewing angles. Some such angles might actually give the most accurate tree top position estimates for spruce and other trees with similar morphology (such as fir).

One main issue in Dralle and Rudemo (1997) was to treat the problem (i) mentioned at the end of Section 1. By use of "ground truth" data and a model for the joint distribution of the two marked point processes, including models for errors of omission and errors of commission, parameters were estimated by maximum likelihood.

FUTURE WORK: THEORETICAL STUDIES OF INCOMPLETELY OBSERVED MARKED POINT PROCESSES

Studies of sequences of images, similar to the study described in Section 3, are presently being undertaken or planned for tracking the development of weed plants (time interval 3 days) and for the growth of forests (time interval 5 years).

Further, there is a clear demand for theoretical studies of the type of problems with pairs of marked point processes described in the present paper. Let us here note some interesting recent studies for models with marked point processes consisting of Gibbs type processes with disks observed in white noise (Baddeley and van Lieshout, 1993; van Lieshout, 1994).

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AN ALGORITHM FOR DELINEATION OF INDIVIDUAL TREE CROWNS IN HIGH SPATIAL RESOLUTION AERIAL IMAGES USING CURVED EDGE SEGMENTS AT MULTIPLE SCALES

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ABSTRACT

This paper presents an automatic multiple-scale algorithm for delineation of individual tree crowns in high spatial resolution aerial images. The tree crown contours were identified as convex zero-crossings which were computed with sub-pixel accuracy on the intensity image for each image scale. The centre of curvature was estimated for every edge segment pixel. For each segment these centre points formed a path (evolute) or swarm which was modelled as a primal sketch using an ellipse extended with the mean circle of curvature. The model described the position or region of the derived tree crown based on the edge segment at the current scale. The sketch was rescaled with a significance value and accumulated for a scale interval. In the accumulated sketch a tree crown segment was grown, starting at local peaks, under the condition that it was inside the area of healthy vegetation in the aerial image and did not trespass a neighbouring crown segment. The method was evaluated by comparison with a manual delineation work and ground truth on 43 randomly selected sample plots. It was concluded that the performance of the method is almost equivalent to visual interpretation. On the average, seven out of ten tree crowns were the same. Furthermore, ground truth indicated a large number of hidden trees on the sample plots. The proposed technique could be used as a basic tool in forest surveys.

Keywords: aerial image, edge detection, grey level curvature, scale space, forestry, remote sensing.

RÉSUMÉ

ALGORITHME DE DÉLIMITATION DES HOUPPIERS DANS DES IMAGES AÉRIENNES À HAUTE RÉOLUTION SPATIALE, À L'AIDE D'UN SEGMENT DE CONTOUR COURBE À ÉCHELLES MULTIPLES

La présente communication porte sur un algorithme automatique à échelle multiple servant à délimiter les houppiers des arbres dans des images aériennes à résolution spatiale élevée. Les contours des houppiers ont été identifiés comme des passages à zéro convexes qui ont été calculés au sous-pixel près sur l'image d'intensité pour chaque échelle d'image. On a fait une estimation du centre de la courbe pour chaque pixel de segment de contour. Pour chaque segment, ces points centraux formaient une voie (développée) qui a été modélisée comme esquisse primaire à l'aide d'une ellipse prolongée avec le cercle de courbure moyen. L'esquisse a été remise à l'échelle avec une valeur significative et cumulée pour obtenir une valeur de division. Un segment de houppier a été dégagé dans l'esquisse cumulée, en commençant aux crêtes ponctuelles, dans les conditions du secteur de végétation saine de l'image aérienne, sans dépasser un segment de houppier avoisinant. La méthode a été évaluée en la comparant avec un travail manuel de délimitation et de vérité-sol sur 43 placettes-échantillons choisies au hasard. On a conclu que la performance de la méthode était presque équivalente à celle de

l'interprétation visuelle. En moyenne, 7 houppiers sur 10 étaient semblables. De plus, les travaux de vérité-sol ont permis de voir un grand nombre d'arbres cachés sur les placettes-échantillons. La technique proposée pourrait être utilisée comme outil de base dans les inventaires forestiers.

INTRODUCTION

Vision is the process of discovering from images what is present in the world and where it is (Marr, 1982). But in an aerial image of a forest a single tree crown may only be discernible as an individual object over a certain interval of scale. At the finer scales all branches are visible and it may not be a simple task to group them correctly together to a single tree crown. On the other hand, at coarser levels of scales, a tree crown may have merged together with its neighbours. At these scales one would talk about an image of a forest rather than an image of trees. Consequently, a multiple scale algorithm is appropriate for the process of delineating individual tree crowns. Scale space theory in computer vision offers a formal mathematical treatment of analysing images at multiple scales (e.g., Witkin, 1983; Koenderink, 1984; Yuille and Poggio, 1986; and Lindeberg, 1994).

In the forestry community, digital remote sensing analysis has often been used for image enhancement followed by on-screen interpretation, but future automated methods will increasingly use many kinds of image information, e.g., boundaries, shape and context (Leckie, 1990). Advance information should be used in the analysis if it is available. For instance, an expected tree crown size interval might simplify the decision process. The crown size is closely related to the appropriate image scale. The interval can often be derived from a forest stand description or a forest map if there is also a rough description of the relationship between the tree crown size and the stem diameter. The geographical site in which the image was acquired is also a clue in this context.

The finer levels of aerial image scale have mainly been used for visual interpretation (e.g., Spencer and Hall, 1988; Hagan and Smith, 1986) for estimating timber volumes and tree species composition. The technique to estimate the size of individual tree crowns by a computerized system is still a future course of action during forest surveys. Some methods for recognition of individual tree crowns have been proposed, e.g., a crown-following approach based on the spectral valleys between tree crowns (Gougeon, 1995) and a vision expert system based on the radial brightness distribution of tree crowns (Pinz, 1989). A three-dimensional crown model for generating a set of image templates can be used for image matching (Pollock, 1996). The number of trees per unit area may be estimated by counting the number of grey level maxima above a certain level of a smoothed image, after the Gaussian kernel bandwidth has been estimated (Dralle and Rudemo, 1996).

This paper presents an algorithm which makes use of edge contours, with convex gray level curvature, at multiple scales for estimating the extent of the tree crowns. The organization of the paper is as follows. First, there is an analysis overview in section two. Then each step of the algorithm is described in section three. Sections four, five and six present an evaluation of the method on a large image data set with ground truth. For reason of comparison this section includes a delineation work made by an experienced visual interpreter. Finally, there is a brief conclusion and a discussion section.

A SYSTEM OVERVIEW

A system overview of the multiple scale analysis of the aerial images includes a colour transform, image smoothing, edge detection, calculation of grey level curvature on the edges, building a primal sketch and accumulating it for a scale interval. Finally, tree crown segments are grown. The procedure of segmenting significant tree crowns was primarily based on scale space theory. It is a frame work for low-level or early image processing.

Image smoothing was performed on the intensity (brightness) image (Gonzalez and Woods 1992, Chap. 4) derived from the colour infrared (CIR) aerial image. Intensity edges were detected as zero-crossings (Canny,

1986; Yuille and Poggio, 1986) which have sub-pixel accuracy. Only edges with convex grey level curvature were further processed.

At each image scale and for each edge pixel a centre of curvature was computed from the grey level curvature data. All such points belonging to the same edge segment formed a path (evolute) or swarm. An ellipse model was estimated based on these points and it was extended with the radius of the mean circle of curvature. An exponential function formed a model of the region and it was used as a primal sketch (Marr, 1982). A significance value rescaled the values of the primal sketch and they were accumulated.

Local peaks were detected in the accumulator and if they were above a certain significance threshold they were selected as seed points for the tree crowns. The tree crown segments were grown simultaneously from each seed point. They were not allowed to grow into other segments or to grow outside the large healthy vegetation segment.

The algorithm was evaluated on 43 sample plots randomly selected from 86 plots on 24 different images. The aerial images were acquired in central Sweden on productive forest land. On each sample plot, ground truth was available. On a corresponding and larger image plot a delineation work made by an experienced visual aerial image interpreter was available.

THE DELINEATION ALGORITHM

The different steps of the algorithm are described in detail in this section, together with exemplifying pictures and sketches of the image processing. A subimage of one of the aerial images is used as a running example (Figure 1).

IMAGE SMOOTHING

The purpose of smoothing is to round-off the contour of each individual tree crown and merge different contour parts that are close to each other. Furthermore, the smoothing identifies those edge contours that obviously belong to the same circular tree crown. As crowns are of different sizes and shapes, smoothing must be at different degrees. Image isotropic smoothing was based on a family of discrete kernels. The image representation L at scale level t ($t=\sigma^2$) was given by Lindeberg (1990):

$$L(x, y; t) = \sum_{m=-\infty}^{\infty} T(m; t) \sum_{n=-\infty}^{\infty} T(n; t) f(x - m, y - n) \quad (1)$$

where $T(n; t) = \exp(-t) I_n(t)$ and I_n is the modified Bessel function of integer order n . The modified Bessel functions are not always available as standard routines. One must then use an algorithm to generate the required filter coefficients $T(n; t)$ for a scale value t and one such algorithm was specified in Lindeberg (1988). The smoothing was light, $t=9.0$ up to approximately $t=36.0$, for merging tree crown parts that were already close to each other.

EFFECTIVE SCALE

To be able to appropriately compare and sum up the primal sketches at different levels of scale, the notation of effective scale (Lindeberg, 1993) was adopted. It is based on the assumption that the probability that a local extreme, which in this analysis could be a convex tree crown edge, disappears during a short scale interval should not vary with scale. If the expected density $p(t)$ of extreme points at a certain level of scale is known, the effective scale τ as a function of the ordinary scale parameter t , can be written as:

$$\tau = A + B \times \log(p(t)) \quad (2)$$

The density $p(t)$ of convex edges was investigated for a representative aerial image. A function was estimated by regression analysis by letting the logarithm of the scale and the density values be the independent

and dependent variables, respectively. The constant A in (2) can be set to zero and the constant B in (2) is just a rescaling of the effective scale parameter (Lindeberg, 1993). With A equal to zero and B equal to one, the effective scale parameter τ was given by:

$$\tau = -1.6003 - 0.2348 \times \log(t) \quad (3)$$

The effective scale was incremented with equal step length using the relationship in (3) and the t values calculated in this way were used in the image smoothing process.

A DIFFERENTIAL GEOMETRIC DEFINITION OF EDGES

Edges in a digital image may be defined in many different ways. For the continuous case, it is natural to define edges as those points where the gradient magnitude assumes a maximum in the gradient direction (Lindeberg, 1994). This method is called non-maximum suppression (e.g., Canny, 1986). Edges, which represent tree crown contours in our aerial images, are defined by a differential geometric approach. Therefore, a new orthonormal coordinate system (u, v) , at any image point, is introduced, where the v -axis is parallel to the gradient direction of the brightness L in the current point, and the u -axis perpendicular to it. Thus, the u -axis is parallel to the tangent of the level curve. The local directional derivative operators in this new coordinate system are related to the Cartesian coordinates as:

$$\partial_u = \sin \beta \partial_x - \cos \beta \partial_y \text{ and } \partial_v = \cos \beta \partial_x + \sin \beta \partial_y \quad (4)$$

At an arbitrary image point the gradient magnitude is equal to L_v . It is assumed that the second- and third-order directional derivatives of L in the v -direction are not simultaneously zero. The condition for an image point to be a gradient maximum, i.e., an edge point, in the gradient direction is given by:

$$L_{vv} = 0 \text{ and } L_{vvv} < 0 \quad (5)$$

A change of the coordinate system, from the curvilinear system to the Cartesian system, using the relationship in (4) above, gives:

$$L_{vv} = \frac{L_x^2 L_{xx} + L_y^2 L_{yy} + 2L_x L_y L_{xy}}{(L_x^2 + L_y^2)^2} = 0 \quad (6)$$

$$L_{vvv} = \frac{L_x^3 L_{xxx} + 3L_x^2 L_y L_{xxv} + 3L_x L_y^2 L_{xyv} + L_y^3 L_{yyy}}{(L_x^2 + L_y^2)^3} < 0 \quad (7)$$

Using these equations, it is a simple task to find edge points. Note that the edge points (zero-crossings) are a sub-pixel entity. No thresholding on the gradient magnitude was performed. To simplify the subsequent treatment of the edge segments there was no application of any interpolation scheme. All 8-connected neighbouring pixels on the negative and positive side of the zero-crossing, respectively, formed an edge segment.

ESTIMATION OF GREY LEVEL CURVATURE ON THE EDGES

A useful entity often used for corner detection is the curvature κ of grey level curves in the smoothed image L (Lindeberg, 1994):

$$\kappa = \frac{L_x^2 L_{yy} + L_y^2 L_{xx} - 2L_x L_y L_{xy}}{(L_x^2 + L_y^2)^{1.5}} \quad (8)$$

The curvature was calculated on the zero-crossings and a threshold ensured that only convex ($\kappa < 0$) sections were processed further. Additionally, a convex section was removed if its sector angle, relative to its mean centre of curvature, corresponded to less than $\pi/4$. Edge segments were also removed if they consisted of less than ten pixels. Figure 2 shows the contours with convex gray level curvature at scale level $t=12.0$ approximately for the subimage.

PARAMETERS DERIVED FROM THE CURVATURE DATA

The parameter *average curvature* can be derived from the curvature values for each convex edge segment. In the continuous case, it is defined as (van der Heijden 1994):

$$\bar{k} = \frac{1}{L} \int_{s=0}^L k(s) ds \quad (9)$$

where L is the length of the segment $k(s)$ is the curvature at point s and s is the running arc length from start point to end point. Due to the digital nature of the image and the fact that the edge points (zero-crossings) are sub-pixel entities, this equation was reformulated as:

$$\bar{K} = \frac{1}{N} \sum_{i=1}^N k_i \quad (10)$$

where N is the total number of edge pixels in the current segment and k_i is the curvature at edge pixel number i . The distance between edge pixels is thus always counted as one, and the edge was formed by the pixels on the positive and negative side of the zero-crossings, respectively. The *average curvature* gives an estimate of the *mean radius of curvature* (e.g., Mokhtarian and Mackworth 1986):

$$\rho = \frac{1}{\kappa} \quad (11)$$

TRANSFORMATION PROCESSES IN SCALE SPACE

An edge contour normally goes through at least one of the following four transformation processes when blurring is gradually increased: 1) 'Rounding-off', 2) 'Expansion', 3) 'Transformation into circles', and 4) 'Merger' (Bergholm 1987). The centres of curvature belonging to the edge pixels will be transformed analogously. If the expected tree crown size interval and the digital nature of the images are taken into account, there are mainly five cases: 1) 'Move position', 2) 'Merge' or 3) 'Split' relative to neighbouring centres of curvature, 4) 'Show up' or 5) 'Disappear'. The expected tree crown size interval will influence 4) and 5).

The smoothing process starts at scale level $t=9.0$. It was motivated by the fact that a merger between two closed contours takes place when the t -value is about equal to the distance between them (Bergholm, 1987). In the finer levels of scale (less than $t=9.0$, approximately), the fine structures predominantly represent internal tree crown branches. The scale space technique in this algorithm is focusing on the tree crown contours, which mainly undergoes rounding-off transformations at higher levels of scale. Therefore, no loss of essential information was expected to take place due to the heuristically chosen and applied scale interval.

THE CENTRE OF CURVATURE PRIMAL SKETCH

A primal sketch (Marr, 1982) may describe significant image intensity changes. It may also be used analogously for describing significant curvature changes of contours (Asada and Brady, 1986), based on primitives like corner and smooth join. A similar modification of the original term primal sketch is introduced here. An appropriate name of the modification is the *centre of curvature primal sketch*.

At each edge pixel P in a segment, a curvature value was calculated using eq. 8. The circle of curvature at point P is a circle tangent to the curve at point P whose centre, (ξ, η) (Figure 3), lies on the concave side of the curve and whose curvature is the same as that of the curve at point P (Mokhtarian and Mackworth, 1986). The path of all centres of curvature of an edge segment is called the *evolute*. For a circle the evolute is mapped into the same point (origin). For an ellipse contour the evolute is a path in the xy-plane having a specific position.

In our algorithm the radius of the mean circle of curvature ρ and the gradient direction at each edge pixel were used to find a modified evolute. Only reasonable radius were considered further ($\rho < 5.0$ m). The points of the evolute from an edge contour segment were modelled with an ellipse by using a sample covariance matrix S, with the coordinate pair of the centre of curvature as a two-dimensional variable. Principal component analysis (Jolliffe, 1986) was used to find the major and minor axis of the ellipse. The (j,k) th matrix element of the sample covariance matrix S was the estimated covariance between the i th and j th elements, and the variance of the i th element when $i=j$:

$$s_{jk} = \frac{1}{N-1} \sum_{i=1}^N (x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k) \quad (12)$$

where $j, k = 1, 2$ and the coordinates for the centre of gravity of the N evolute points were given by:

$$\bar{x}_j = \frac{1}{N} \sum_{i=1}^N x_{ij} \quad (13)$$

The orientation of the first principal component (major axis) was given by:

$$\phi = \arctan\left(\frac{s_{12}}{s_{22} - s_{11}}\right) \quad (14)$$

The area of the ellipse models a scatter plot of all the evolute points. The two-dimensional Gaussian function with standard deviation σ can be separated into the product of two one-dimensional functions (Williams and Shah, 1990) and in a similar way be applied here. The square root of the calculated eigenvalues of (12) σ_1 and σ_2 , extended with the value of the mean radius of curvature ρ , formed the major and minor axis (2a and 2b) of the model. The product of two one-dimensional and perpendicular models formed the basis of the two-dimensional primal sketch. Centred at the current mean centre of curvature the model was given by:

$$h(x, y) = \frac{\rho^2}{(ab)} \times \exp(-\text{constant} \times (\frac{x^2}{a^2} + \frac{y^2}{b^2})) \quad (15)$$

where *constant* = 2.0 for good segmentation results. At the centre of gravity of the ellipse the values of the exponential term were close to one, and it decreased towards the edge of the ellipse region. If σ_1 and σ_2 were low, the scaling factor before the exponential term was almost one. The derived sketch indicated where one could expect to find the visible tree crown computed from the visible tree crown edge.

The primal sketch was rescaled by a significance value. It was computed from the quotient of the sector angle relative to the mean centre of curvature and a whole circle (Figure 3). Finally, the calculated model was added to a primal sketch accumulator. Figure 4 shows the primal sketches of the subimage at scale level $t=12.0$ and Figure 5 the accumulated (scale levels from $t=9.0$ to approximately $t=36.0$) sketches.

The accumulator was smoothed by a Gaussian kernel with a small t -value (In this work $t=5.0$.) for merging close peaks. This procedure corresponded to merging several tree crowns standing very close together into a single tree crown. Local maximal values were identified in the accumulator. A threshold ($T=0.05$) ensured that only points with high values were selected.

TREE CROWN SEGMENTS

The goal of the image analysis is delineated individual tree crowns. This can be achieved by first using a global threshold in the image. The threshold should in some optimal way identify the delimiter between vegetation (all healthy tree crowns) and nonvegetation or the dark background. The latter group includes stones and soil on the ground, dead vegetation and other nonliving objects. The thresholding is feasible because of the higher spectral reflectance of the healthy vegetation in the near infrared band of the aerial image (Harris, 1987), which will affect the local intensity of the aerial image.

Simple image statistics can be used for estimating a global threshold value (Kittler et al., 1985), based on the pixel brightness weighted with the gradient magnitude in an ideal two brightness level image:

$$T = \frac{\sum_{i=1}^N \sum_{j=1}^N |h_{ij}|}{\sum_{i=1}^N \sum_{j=1}^N |e_{ij}|} = \frac{B + D}{2} \quad (16)$$

where h is the product of the grey level and the gradient magnitude, e is the gradient magnitude and the objects and background pixels have ideal grey level values B and D , respectively. N represents the image size in number of pixels. Under the assumption that B and D do not vary over the image, this equation is the appropriate threshold value for segmenting objects from the background.

Unfortunately, the brightness of the tree crown objects in an aerial image is not ideal, especially if there is low elevation sun. Generally, there is a sunny side and a dark side of the tree crown. Therefore, a more suitable, but similar, method was developed. According to (5) the tree crown contour was the points where $L_{vv} = 0$. Furthermore, L_{vv} can be expected to be negative inside the tree crown and positive outside at scale level $t=9.0$. L_{vv} is always negative inside and close to the steep edges and the gradient magnitude is always high there. Thus, these points were expected to be counted with higher weights. A grey level histogram was formed for the whole image where $L_{vv} < 0$ by incrementing the appropriate grey level with the e values. This distribution was further processed and it was approximately normal distributed around the mean, with an estimated standard error. An interval of confidence was formed (90 %) and the lower limit was used as a threshold for a global segment in the image.

In the image of the accumulated primal sketches each tree crown was visible as a local maximal point with a neighbourhood with decreasing values. Each detected peak represented a seed point for a tree crown segment if the significance value was high. The global segment was 4-neighbourhood eroded (van der Heijden, 1994) three times before the subsequent process. Starting at the seed point the region was grown inside the global segment as long as the values were decreasing and did not contradict with neighbouring segments. The identified and labeled tree crown segments were grown into the previously eroded regions in the end (Figure 6).

AERIAL IMAGE DATA SET

The delineation technique was evaluated on an aerial image data set. The set consisted of 50 colour infrared images acquired as a sample in central Sweden (62°27'N, 16°55'E), on 10 August 1995, between 13:00 and 14:30 p.m. The altitude was 600 m above the ground and the image scale was approximately 1:2000 (focal length: 302.97 mm). The forest stands were older than 40 years. They were mainly mature with an average age of approximately 80 years and mainly natural regenerated in the beginning of the 20th century. The stands were both mixed and pure forest stands and consisted predominantly of Scots pine (*Pinus silvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), birch (*Betula pubescens* Ehrh.) and some aspen (*Populus tremula* L.). The central squares (7.5 cm and 5000 pixels) of the original aerial images (23 cm), Kodak Aerochrome Infrared Film 2443) were scanned. It was motivated by the near orthogonal projection of the whole image. That is, all the tree crowns were observed almost straight from above. The images were resampled by bilinear interpolation (Gonzalez and Woods 1992) to a pixel size corresponding to 10 cm on the ground. The final size

of the images corresponded to a square of 120 meters. The algorithm was implemented in the Khoros Software Package, version 2.1.

GROUND TRUTH AND VISUAL INTERPRETATION

Ground truth were measured on 86 sample plots (radius 10 m) on 24 images during the summer of 1996. The plots were randomly positioned with a square spacing (50 meters) relative the centre of the aerial image. The latter position was identified using a Global Positioning System (GPS) and manual recognition of the trees on the ground. A set of 43 randomly selected plots out of 86 was used in the evaluation of the delineation algorithm. The composition of the tree species on the 43 sample plots was Scots pine 23 % of the total stem volume, Norway spruce 62 % and birch 14 %. Aspen was less than 1 %.

For comparison with the accuracy achieved by a human interpreter, which is still the prevalent method, an experienced aerial image interpreter made a manual delineation work on the corresponding image subset. The interpretation was performed on a slightly larger subimage (radius 12 m) than the sample plot for better visibility.

EXPERIMENTAL VALIDATION ON IMAGE AND FIELD DATA

The algorithm was evaluated on the 43 randomly selected sample plots. A summary of the different segment configurations for each tree species compared with the segment configurations made by the manual interpreter is presented in Table 1. A lot of small tree crowns were identified by the human interpreter, but our computerized system ignored them due to the selected global threshold value. Some distinct tree crowns were not identified during the visual interpretation. But they were found by our system. A lot of light sun patches were found by the computer, but the human interpreter could discriminate them.

Tree species	3:1	2:1	1:0	1:1	0:1	1:2	1:3
Scots pine	4	18	1	201	12	34	2
Norway spruce	4	35	9	483	144	55	9
Birch	8	29	2	130	15	21	3
Aspen	2	5	0	14	4	1	0
TOTAL	18	87	12	828	175	111	14

Table 1. Delineation results made by our system on the 43 randomly selected sample plots (radius 12 m) compared with manual interpretation. The table lists different classes of segment configurations made by our system relative to manual delineation and the number of occurrences for each class.

Table 2 shows a summary of the performance compared with ground truth. Light sun patches (approximately 23) on the ground were not included. Note that Table 1 and Table 2 are approximate values, derived from an assessment of the configuration of each image segment.

Tree species	3:1	2:1	1:1	0:1	1:2	1:3
Scots pine	4	6	84	9	26	6
Norway spruce	1	22	282	99	89	11
Birch	6	22	105	4	52	8
Aspen	2	6	2	0	7	0
TOTAL	13	56	472	112	174	25

Table 2. Delineation results made by our system on the 43 randomly selected sample plots (radius 12 m) compared with manual interpretation. The table lists different classes of segment configurations made by our system relative to manual delineation.

The relation between the number of tree crowns identified on the sample plots (radius 10 m) by the algorithm and the number of trees (diameter at breast height greater than 10.0 cm) measured on the ground is presented in Table 3.

35-	40-	45-	50-	55-	60-	65-	70-	75-	80-	85-	90-	95-
2	5	4	6	4	7	8	1	2	1	2	0	1

Table 3. The total number of plots (43) distributed on different tree count groups. Each group (%) defines a 5%- class, which is the number of segments identified by the algorithm relative the number of trees (diameter at breast height greater than 10 cm) counted on the ground.

On the average, for the whole analysed data set, the average crown diameter visible in the image was 54% of the corresponding physical tree crown diameter on the ground.

CONCLUSION

Our algorithm was able to capture circular and elongated tree crowns if the solution did not contradict with other neighbouring tree crown segments. The delineation results were almost equivalent to the manual delineation work, and if the classes 1:2 and 2:1 in Table 1 cancel each other, the results are very good.

The ground truth indicated a lot of hidden trees or trees standing very close to each other that were not visible in the aerial images. Compared with the ground truth the segmentation process was often not able to discriminate trees standing very close to each other. On the average 54 % of the physical tree crown diameter on the ground was visible in the image. This was caused by overlapping crowns and light conditions.

One drawback with the low dynamic range of the infrared photographic film was that the shady side of a large tree crown (e.g. spruce) was completely dark. Using the convex edge segmentation method presented here, this limitation was partly circumvented. The combination of the edge detection for estimating tree crown shapes and extension and the global threshold value for identifying the brightness delimiter between the background and the objects was proved to be very applicable. The estimate of the global threshold value was without remark for all analysed images.

Light sun patches on the ground were identified as tree crowns in many cases. These segments must be classified in a subsequent analysis, e.g., by using colour or possibly a shape measure.

The presented algorithm is suited for identifying individual tree crown regions, useful for example species classifications. The spatial relationship between segments must be considered.

DISCUSSION

The underlying tree crown model in the scale space search for tree crowns was in principle a circular model. But ellipse-shaped crowns could be found in some cases, if that was the best solution. The general tree crown model was based on the fact that an undamaged tree has a major stem and the branches grow radially out from the stem. A natural forest contains a lot of broken and leaning trees, which makes the analysis very difficult and there are a lot of cases when a false identification of the tree crowns occurred.

Generally, a sample image often contains trees of almost the same size due to the low spatial variation in the forest stands. The delineation process should pay more attention to large trees because they contain most of the stem volumes and are more valuable. The illumination and visibility should be similar for the same class of forest stand and the segmentation algorithm can be expected to perform equally on the average on images of the same class of forest. Furthermore, if the forest is dominated by trees of the same size class, it could be possible to replace the heuristically chosen smoothing interval by an interval derived from features of the objects in the image.

The accumulated sketch can also be used as input to another higher level algorithm, such as snakes (Kass et al., 1987), which needs a closed initial contour. The algorithm combined with the simple global threshold estimation fulfilled most of our segmentation requirements and solved the multiple scale property of the tree crown contours.

An important feature of the mature forest is that there is often a visible dark spacing between tree crowns in the aerial image. It might be very narrow and it might be the result of waving trees in the wind. This feature was often useful for the edge detection process.

Further developments may use information derived from the segmentation algorithm. Such data are the estimated tree stem position and estimated tree crown shape and overlap. Further research work will use the crown segments as regions of interest (ROI) for internal structure analysis (e.g., Brandtberg, 1997). Together, they will be used for species classification, and if the analysis includes spatial relationships between segments, it might be possible to estimate stem diameter accurately. Tree height data could also be included from, for example, an airborne laser scanner for estimating stem volumes.

The research work concerning digital image analysis of aerial images presented here presumes that the photographic film is replaced by a digital camera in the future. It is expected to be much more cost effective and to have very good sensitivity and high dynamic range.

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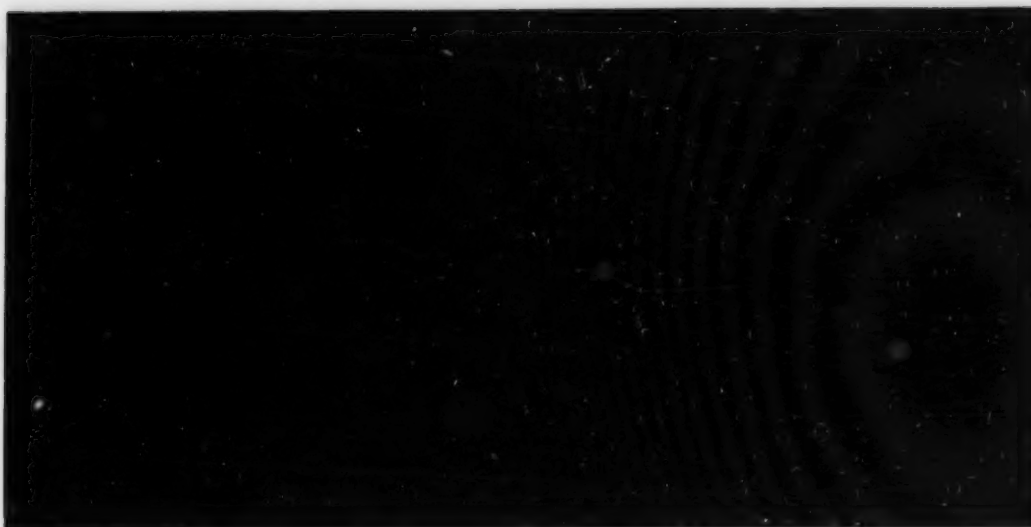


Figure 1. (left) and **Figure 2.** (right) Original intensity aerial image (left) of predominantly Scots pine and corresponding curved edge segments (right) at scale level $t=12$, approximately. A dark edge pixel corresponds to a low grey level curvature. (Image size 40 m and pixel size 10 cm.)

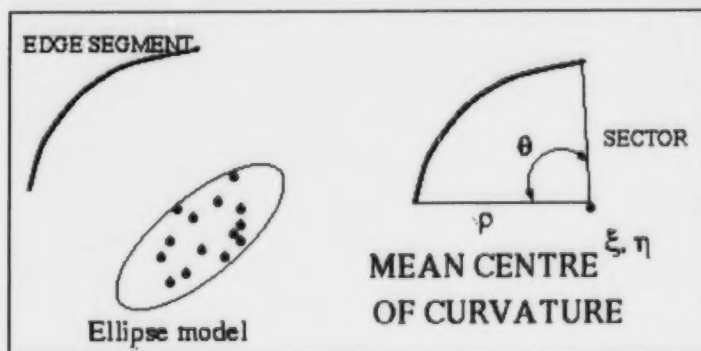


Figure 3. A centre of curvature ellipse model derived from an edge segment (left). The mean centre of curvature (right) and the sector angle used for rescaling the model.



Figure 4. (left) and **Figure 5.** (right). Primal sketches (left) for the subimage at scale level $t=12$, approximately. Accumulated primal sketches (right) for the whole scale interval ($t=9.0$ to $t=36$). Note that the maximal value in Fig. 4 is equal to or less than one and the maximal value in Fig. 5 is probably greater than one.

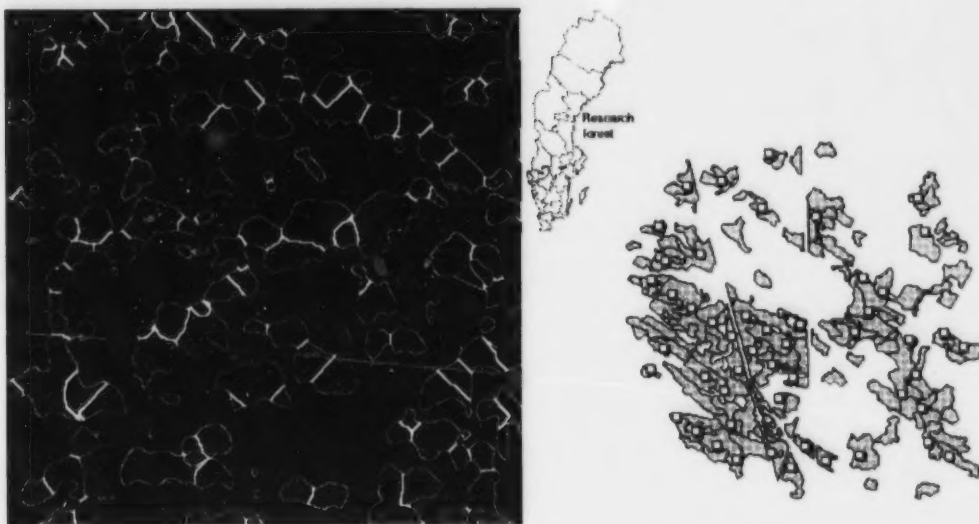


Figure 6. (left) and **Figure 7.** (right). Segments (left) for the subimage with white borders. The research forest (right) and its site in the middle of Sweden. The 50 squares correspond to the positions of the acquired aerial images within the forest area (25 km^2).

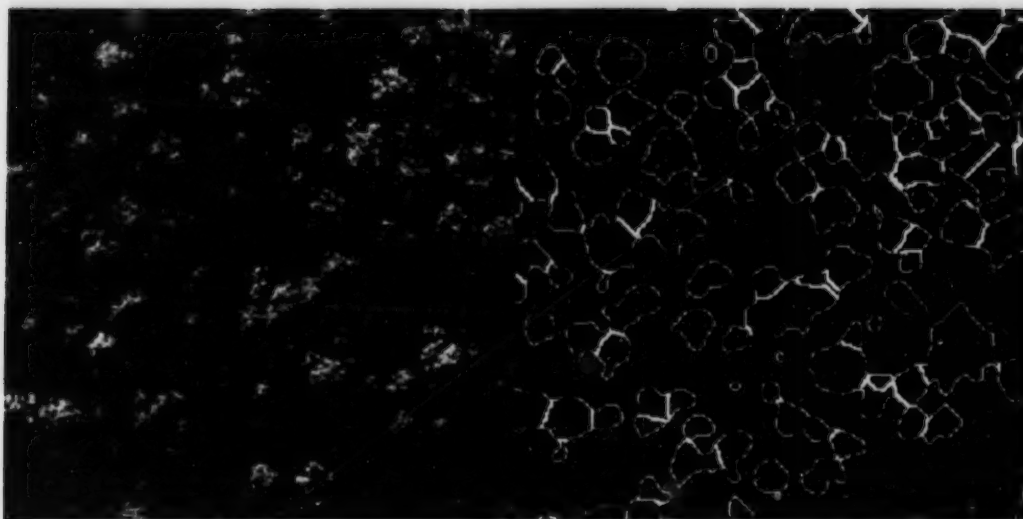


Figure 8. (left) and **Figure 9.** (right) Another subimage (left) with predominantly birch and corresponding segments (right). Different species and individuals result in a better segmentation.

FINDING AN OPTIMAL MATCH WINDOW FOR SPRUCE TOP DETECTION BASED ON AN OPTICAL TREE MODEL

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ABSTRACT

A method for detecting Spruce tree tops in high resolution panchromatic images at acute angles has earlier been reported. The method uses an optical tree model and flight data to generate a template tree image, i.e., an image of what the "average" tree would look like if placed at a certain point in the imaged scene. A window into the template image is matched to the actual forest image by at each pixel computing the correlation of the local intensity values. Local maxima in the resulting correlation image correspond to high similarity with the template image and thus correspond to positions where there might be a tree. It is clear that the shape and size of the match window and its placement within the template image has an impact on the performance of this tree top detection algorithm. For a specific parameterisation of the match window shape, size and placement, and a specific set of images where the real tree positions are known one can find an empirical optimum for the average performance of the algorithm over the images. Such an examination for images of an even-aged pure Spruce stand yielded surprising results: the optimal size was significantly smaller than expected and the optimal shape close to a circle. By using the estimated optimal parameter values rather than those used in the work earlier reported, the tree top detection rate was increased from 85–92% to 91–98%.

Keywords: aerial photographs, template matching, tree crown modelling, forestry, Norway spruce.

RÉSUMÉ

ÉTABLISSEMENT D'UNE FENÊTRE D'APPARIEMENT POUR LA DÉTECTION DES HOUPPIERS D'ÉPINETTES, D'APRÈS UN MODÈLE OPTIQUE D'ARBRE

On a déjà fait état d'une méthode de détection des houppiers d'épinettes sur des images panchromatiques à haute résolution prises à angles aigus. La méthode repose sur l'utilisation d'un modèle optique d'arbre et de données de vol pour générer une image de modèle d'arbre, c'est-à-dire une image de ce à quoi ressemblerait un arbre "moyen" s'il était placé en un certain point de la scène imagée. Une fenêtre pratiquée dans l'image du modèle est appariée à l'image de la forêt réelle à chaque pixel, en calculant la corrélation des valeurs locales d'intensité. Les maximums locaux dans l'image de corrélation résultante correspondent à peu près en tout point à l'image du modèle et, par conséquent, à des positions où il pourrait y avoir un arbre. Il est clair que la forme et les dimensions de la fenêtre d'appariement ainsi que sa position sur l'image du modèle ont une incidence sur la performance de cet algorithme de détection des houppiers. Pour obtenir une paramétrisation spécifique de la forme, des dimensions et de l'emplacement de la fenêtre d'appariement et l'obtention d'un jeu d'images spécifiques où l'emplacement précis des arbres est connu, on peut trouver une valeur optimale empirique de performance moyenne de l'algorithme sur les images. Un tel examen des images d'un peuplement pur d'épinettes équiennes a donné des résultats étonnants qui sont présentés dans ce document. En utilisant les

valeurs paramétriques optimales estimées plutôt que celles qui ont été utilisées dans le rapport mentionné précédemment, le taux de détection des houppiers est passé de 85 %-92 % à 91 %-98 %.

INTRODUCTION

The problem of locating individual trees in aerial photos has recently been studied by several workers (Pollock, 1994a; Pollock, 1994b; Gougeon, 1995; Pollock, 1996; Dralle and Rudemo, 1996; Dralle and Rudemo, 1997; Dralle, 1997; Larsen and Rudemo, 1997; Larsen, 1997).

Smoothing by convolution with isotropic Gaussian kernels with suitably chosen standard deviations was used to estimate the number of trees per hectare from aerial photographs of Spruce stands (Dralle and Rudemo, 1996) and to estimate individual tree positions (Dralle and Rudemo, 1997). The method was found to perform satisfactorily for trees reasonably close to the nadir point in the photograph (Dralle, 1997). For photogrammetric estimation of the individual tree heights however, it is necessary to be able to estimate individual tree top positions from a variety of off-nadir angles.

The approach described in the present paper was first presented in Larsen and Rudemo (1997) and later modified in Larsen (1997). It is based on tree crown image templates from a geometric-optical model.

THE OPTICAL MODEL

The optical tree model is that used in Larsen (1997), which is an extension of the model used in Larsen and Rudemo (1997), which in turn extends the model in Pollock (1994a; 1994b; 1996) by including background to the modelled tree crown. The basic elements are a single tree crown, a "ground" plane, light sources and a camera.

LIGHT SOURCES AND CAMERA

Only the sun and the (clear) sky are considered. The diffuse illumination from the ground and from inter-reflections between trees in the stand is ignored.

The sun is modelled as a collimated beam of light. The direction to the sun is computed from the time and place of image acquisition.

The clear sky is modelled as a number of discrete collimated light beams emanating from directions evenly distributed over the sky (hemi)sphere as suggested in Woodham and Gray (1987). Although the directional distribution of light in the clear sky is not uniform, a uniform distribution is used here, and more importantly, the shadowing by neighbouring trees is not taken into account. The power of the sun relative to the clear sky is set to 1.6 based on light/shadow contrasts in the images used.

The camera is assumed to be a pinhole camera. Its location, resolution, the direction of the optical axis and the "up" direction in the image plane are computed from the image rectification parameters (Dralle, 1997).

TREE CROWN SHAPE

The basic tree crown shape is modelled as a *generalised ellipsoid* that in (x,y,z) coordinates has the surface

$$\frac{(z^2)^{\frac{n}{2}}}{a^n} + \frac{(x^2 + y^2)^{\frac{n}{2}}}{b^n} = 1 \quad (1)$$

where z is the vertical axis, the "centre" of the tree crown is at the origin, a is half the height of the ellipsoid, b is half the radius and n is a shape parameter.

The crown ellipsoid can be truncated downwards by a horizontal plane intersecting the vertical axis at $z = z_{\text{base}}$, $-a \leq z_{\text{base}} < a$. This is especially relevant for Spruce or Fir, where in this work only the upper half of the ellipsoid is used.

CROWN AND LIGHT INTERACTION

The interior of the tree crown is assumed to contain randomly oriented scatterers (needles, twigs, *et cetera*). The scatterers can be of several different types $t \in T$ having different optical properties and distributions. Their density within the tree crown envelope is assumed proportional to a function $f^{(t)}(r) \geq 0$, $r = (x, y, z)$, such that the proportion of a ray of light that will pass without interaction (be transmitted) through a volume containing foliage is given by

$$p_{tr}(L) = \exp\left(-\int_L \sum_{t \in T} f^{(t)}(r) dw\right) \quad (2)$$

(Beer-Lambert's Law). The integral is over the path L of the ray through the volume, with $r = r(w)$. The light not transmitted will be either absorbed or reflected by the scatterers. Only *single reflections* are modelled, so the proportion $p_{refl}(r)$ of non-transmitted light isotropically reflected in a small volume around r is equal to

$$p_{refl}(r) = \frac{\sum_{t \in T} p_{refl}^{(t)} f^{(t)}(r)}{\sum_{t \in T} f^{(t)}(r)}, \quad (3)$$

where $p_{refl}^{(t)}$ is the reflectivity factor for the scatterers of type t .

If C is the path of a camera ray through the tree crown, and P_i is the power per unit area perpendicular to the beam direction of light source i , then the power per unit area $P(C)$ of the light reflected by the tree crown in the direction of that camera ray is

$$P(C) = K_{refl} \sum_{i \in \text{lights}} P_i R(i, C), \quad (4)$$

$$R(i, C) = \int_C p_{tr}(C_s(r)) p_{tr}(L_i(r)) p_{refl}(r) \left(\sum_{t \in T} f^{(t)}(r) \right) \left| \frac{dr}{dw} \right| dw, \quad (5)$$

where K_{refl} is a constant giving the proportion of the total reflected light which is reflected towards the camera, $C_s(r)$ is the sub-path C of towards the camera from the point $r = r(w)$ on C and $L_i(r)$ is the path through the tree crown from r towards light source i (see Figure 1).

CROWN COMPOSITION

As in Larsen (1997), where more details are given, it is assumed that the crown of a Norway spruce consists of two types of scatterers: *needles* and *branches*. The density of needles within the crown is given by

$$f^{(needles)}(u) = \begin{cases} c_0 \left(\frac{u}{u_d}\right)^{c_1} \left(1 - \frac{u}{u_d}\right)^{c_2} & 0 \leq u \leq u_d, \\ 0 & \text{otherwise,} \end{cases} \quad (6)$$

where u is the horizontal distance from the closest point on the tree crown envelope and u_d is the maximum depth of live needles within the tree crown. The parameters $c_0 > 0$, $c_1 > 0$, and $c_2 > 0$, are determined from u_d together with the depth of maximum needle density $u_{\max}$, the average needle density f_{avg} and the maximum needle density $f_{\max}$ (Pollock, 1996). In the present work the values $u_d = 2\text{m}$, $u_{\max} = 0.5\text{m}$, $f_{\text{avg}} = 1$, and $f_{\max} = 2$ are used, based on information found in Oker-Blom and Kellomäki (1982) and Koppel and Oja (1984). The panchromatic reflection factor $p_{\text{refl}}^{(needles)}$ is set to 9% based on Williams (1991).

The density function for the scatterers corresponding to the branches is set to

$$f^{(br)}(v) = c_3 \exp(-c_4 v^{c_5}), \quad (7)$$

where v is the horizontal distance from the vertical axis of the tree crown divided by the radius of the tree crown envelope at that point, $0 \leq v \leq 1$. The parameters $c_3 > 0$, $c_4 > 0$, and $c_5 > 0$ are computed from the desired values of $f^{(br)}(0.1)$, $f^{(br)}(0.3)$, and $f^{(br)}(0.6)$, corresponding roughly to trunk, large branches and small branches. In this work the densities 0.5, 0.08 and 0.02 respectively were used. The panchromatic reflection factor $p_{\text{refl}}^{(br)}$ was set to 0% to obtain a pure shadowing effect.

THE "GROUND" PLANE

A "ground" plane is included in the model to provide a background for the modelled tree crown, thereby giving a brightness edge at the crown boundary and for some sun angles allowing the modelled tree to cast a shadow in the ray-traced template. The "ground" plane is with properly chosen reflectance parameters a simple way to describe the average effect of the complex background of neighbouring trees partly in light and partly in shadow.

Optically, the "ground" plane is a horizontal Lambertian surface that reflects and absorbs light. The power P_g of the light reflected in the direction of the camera can be computed from the incident angle θ_i of the light from the light source i :

$$P_g(i) = P_i \rho \frac{1}{\pi} \cos(\theta_i) \quad (8)$$

where the reflectance factor ρ should be chosen to yield a "ground" plane reflection corresponding to the average background for tree crowns in the actual image. The values $\rho = 0.014$, $\rho = 0.017$, and $\rho = 0.020$ were used for the three images "120", "124" and "144" respectively (see the section "experiment" below for an explanation of the image numbers).

TEMPLATE MATCHING

The geometric-optical model is used to produce a template image of a single tree as it would look like if it was placed in the centre of the stand. For near-nadir views or for large stands where the viewing angle varies significantly over the stand, it may be necessary to produce several templates for different positions within the stand.

The template is matched to the aerial photograph by computing the local correlation between the image pixel values and the template pixel values for each image pixel position within the stand. A match window determines which part of the template image is used for the computations. The positive local maxima of the correlation image correspond to the locations that resemble the template most closely as seen through the match window. The positions of the local correlation maxima can be translated into candidates for tree top positions as the position of the model tree top in the rendered template and hence relative to the match window is known. The values of the correlation maxima indicate the quality of the corresponding tree top candidates.

MATCH WINDOW SHAPE

In Larsen and Rudemo (1997) and Larsen (1997) the match window was circular and centered on the model tree top. The radius was set to a fixed value based on the density of the stand to be analyzed. The work reported here consists of some experiments with the size, shape and placement of the match window. The hypothesis motivating these experiments is that the most robust and most correct matches are found if the match window shows about as much of the model tree top as is generally visible in the aerial photograph, plus just enough background to clearly show the edges of the model tree crown envelope (i.e. the contrast between the lighted tree top and the darker background).

To test this hypothesis the match window was defined as follows: the rendered model image define the "height" dimension as being in the direction of the projected vertical central axis of the model tree crown and define the "width" dimension as orthogonal to this. Place an ellipse oriented with its principal axes in these two directions and with its centre placed somewhere on the image projection of the vertical axis of the model tree crown. The ellipse can be described by the following three parameters: r , the radius of the circle of equal area, e , the elongation defined as the "width" dimension of the ellipse divided by its "height" dimension, and t , the vertical translation (as a factor of r) down from the tree top of the point which projected into the rendered image becomes the centre of the ellipse. The units r of are chosen so that they correspond to a projection of the ellipse into the plane parallel to the image plane that contains the top point of the model tree crown, i.e., $r = 1.5$ m means that a circle of the same area as the match window will have a radius of 1.5 m at treetop level (See Figure 2 for further explanation).

ELIMINATION OF SPURIOUS CANDIDATES

Usually taking all the correlation maxima will yield too many candidate positions: some spurious candidates occur where a tree top is detected at multiple nearby locations, some correspond to large branches, some to artifacts due to occlusions between neighboring tree crowns and some to minor variations in the image intensity in low-contrast parts of the image. Several possible strategies for retaining as many of the true tree top positions as possible while removing as many false positions as possible were examined in Larsen and Rudemo (1997).

The approximate number of trees in the stand may be known in advance, for example from automatic estimation methods such as the method described in Dralle and Rudemo (1996). In this case the number of candidates to be retained is equal to the expected number of trees, N_{trees} .

In this work the N_{trees} candidates corresponding to the highest correlation values were selected, subject to the restriction that no selected candidate could be closer than a threshold distance d_{min} to a selected candidate of higher correlation value. A greedy algorithm selecting candidates in order of descending correlation and omitting any candidates too close to already selected candidates was used.

EXPERIMENT

Images showing a sub-plot of a thinning experiment in Norway spruce were used for finding an empirical optimum for the match window parameters. The images were acquired about 40 km northwest of Copenhagen from an altitude of 560 m in clear-sky conditions in the morning of August 4, 1994. At image acquisition the trees were 48 years old. The average tree height was 22.7 m and the stem number was 386 trees per hectare. There were $N_{\text{trees}} = 171$ trees visible from the air in the sub-plot. The digital image was scanned from contact prints and the final image resolution obtained was about 15 cm per pixel (see Dralle and Rudemo, 1996 for further details on the image material).

The height of the tree crown base was estimated to 5 m and the radius of the tree crown at the base to one eighth of the tree height, yielding the parameter values $a = 17.7$ m, $b = 2.84$ m in equation 1. The shape parameter n was estimated to 1.6.

Three images were selected from those available: one where the trees were side-lighted by the sun (image "120"), one where they were back-lighted (image "124") and one where the sun was behind the camera (image "144"). The threshold d_{min} was set 1 m to as the shortest distance between two trees in the sub-plot was at least 2 m.

PROCEDURE

Tree base positions measured in the field were extrapolated to average tree top height and superimposed on the images to yield an initial estimate of the true tree top positions. These positions were adjusted by manual inspection of the images to correct for the errors introduced by different tree heights, variations due to wind, and imprecisions in the image rectifications. The resulting tree top positions were used as "ground truth" in the experiment.

A simple procedure was used to match a given set of tree top candidates with the "ground truth": pairs of positions from the two sets were found in order of increasing error distance such that each position in each set was used only once. This procedure was stopped when the error distance in the next match would be greater than or equal to $d_{\text{max}} = 1$ m (this value is equal to what was chosen for the threshold d_{min}). All trees not matched at this point were declared "unmatched".

QUALITY MEASURE

The quality measure used to compare the set of tree top candidates obtained by the automatic method with the "ground truth" tree top positions for a single image was a *modified standard error* measure computed as follows:

$$SE^* = \sqrt{\frac{\sum_{i \in \text{matched}} |x_i - \bar{x}|^2 + n_{\text{unmatched}} d_{\text{max}}^2}{n_{\text{matched}} + n_{\text{unmatched}}}} \quad (9)$$

where the sum is taken over all matched tree tops, x_i is the error vector for matched tree top i , $||\cdot||$ is the Euclidean distance, $\bar{x}$ is the average error vector for all matched tree tops, n_{matched} and $n_{\text{unmatched}}$ are the number of matched respectively the number of unmatched tree tops, and d_{max} is the maximum error accepted in the matching algorithm as outlined above. This error measure takes into account any systematic differences between what the human interpreter perceives as the tree top and what is the tree top according to the method used to produce the tree top candidates.

OPTIMIZATION

To optimize the parameters for the images used in the present study the arithmetic average $SE^*(r, e, t)$ of the modified standard errors (9) for the three individual images was used as the target function to be minimized. The target function was computed for $(r, e, t) \in G$, where G is a suitable grid of parameter combinations:

$$(r, e, t) \in G = \{1.0\text{m}, 1.5\text{m}, \dots, 4.0\text{m}\} \times \{0.5, 0.6, \dots, 1.3\} \times \{-1.0, -0.5, \dots, 2.0\} \quad (10)$$

The minimum of the target function was obtained for $r = 1.5$ m, $e = 1.0$ and $t = 0.0$. Then the target function was computed for a closer grid G_{close} around these values, and a second degree polynomial in r , e and t fitted to the results.

$$(r, e, t) \in G = \{1.25\text{m}, 1.30\text{m}, \dots, 1.75\text{m}\} \times \{0.80, 0.85, \dots, 1.20\} \times \{-0.50, -0.45, \dots, 0.50\} \quad (11)$$

The parameter values which minimized the fitted polynomial were, after rounding to the nearest grid point in G_{close} :

$$r = 1.5\text{m} \quad s = 0.9 \quad t = 0.2, \quad (12)$$

which thus are the parameter values which yield the optimal match window.

RESULTS AND DISCUSSION

The tree top images rendered from the geometric-optical model are shown in Figure 3, with the border of the optimal match window marked in white. The percentage of found trees (matched tree tops) using this match window, the modified standard error SE^* and the standard error obtained by setting $n_{\text{unmatched}} = 0$ in equation (9) are listed in Table 1. The tree top estimates using the optimal match window are shown as dots in Figures 4–6 together with the 1m radius circles corresponding to the accepted deviations from the tree tops found by the human interpreter.

Table 1. Results for the (on average) optimal match window.

	Img. "120"	Img. "124"	Img. "144"	Average
Matched trees, %	91	96	98	95
SE^* (cm)	39	30	31	34
Standard error, matched only (cm)	27	24	28	27

The results with an estimated standard error for the tree top position estimates of the order 25–30 cm and a recovery percent of 91–98% are quite satisfactory. Further improvement should be possible by combining results from several images in a three-dimensional reconstruction of the stand.

It is somewhat surprising that the optimal size of the match window is so small; based on the density of the stand one would think that it would be larger (about 2.9m in radius). This can partly be explained by the oblique viewing angle which with variations in tree height can cause trees to appear closer together than they are. This will tend to severely penalize large match windows as template matching may fail at a tree top where taller trees in front "stick up" inside the match window or even where the tops of shorter trees in back cause the background to be brighter than expected from the model.

Another surprise is that the optimal match window shape is so close to a circle and that the placement of its centre is so close to the tree top. The original reason for allowing the match window to be elongated in the direction of the tree trunk and to be translated downwards was that this would cause a larger proportion of the

area inside the match window to be "tree" rather than "background". This, however, does not seem to be important. Rather it seems that the ratio between "tree" pixels and "background" pixels in the match window should not be too high, and the reason for this may be that matching is done primarily on the contrast between "tree" and "not tree" and less on the brightness variations within each tree crown. This means that the shape of the model tree crown envelope is perhaps more important than the distribution of optical elements within it.

For the back-lighted trees (image "124") it even seems that it would be slightly better to use a match window which is slightly elongated in the direction orthogonal to the tree crown axis (i.e., wide rather than long) and translated upwards (away from the tree) rather than downwards! This oddity may be caused by the fact that the large contrast between lighted tree tops and background shadow in this image in extreme degree penalizes match windows which are too large in the vertical direction and thereby include not only the target tree but also taller trees in front.

In this experiment, the global optimal match window does not perform much worse than match windows adapted to the individual images, but in general it must be expected that the optimal match window will vary with viewing angle and stand density. Without knowing the "ground truth" like in the experiments here the empirical parameter optimum can of course not be found and the match window parameters must be chosen in some other way. Using a larger set of images and "ground truth" data including different tree densities it may be possible to find how the match window parameters should vary with the geometry at image acquisition, the tree density and the expected tree height variation.

CONCLUSIONS

The optimal size, elongation and placement of an elliptical match window used with a geometric-optical model to find tree top positions in high resolution aerial photos have been estimated for a plantation of Norway spruce with heavy thinning. The optimal parameters seem fairly stable with respect to variations in the geometry at image acquisition.

The optimal size is smaller than could be expected from the stand density, the optimal shape close to a circle and the optimal placement of the centre close to the model tree top. These somewhat surprising results are attributed primarily to variations in tree height within the stand.

The tree top detection rate achieved is 91–98%, depending on viewing angle.

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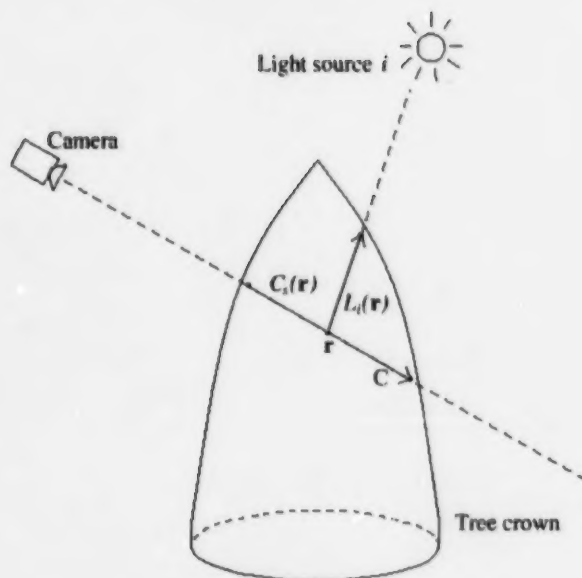


Figure 1. Illustration of the elements in equation 5.

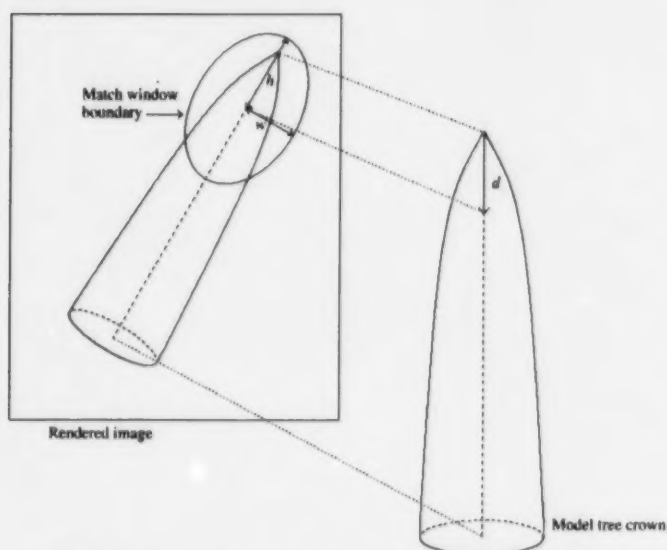


Figure 2. Illustration of the geometry of the match window. In the parameterisation used the three parameters, and are found from the lengths shown in the figure as follows: $r = \sqrt{wh}$, $e = w/h$ and $t = d/r$. The units of the distances w and h (and thereby r) are selected so that they correspond to a projection of the ellipse into the plane parallel to the image plane that contains the top point of the model tree crown envelope.

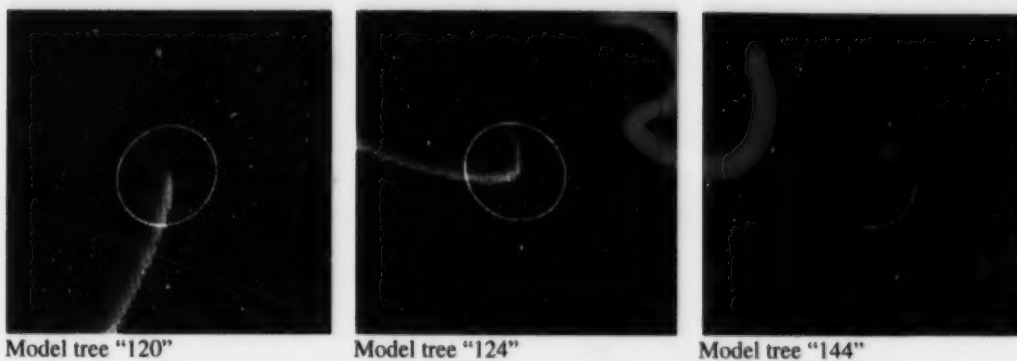


Figure 3. Parts of the rendered synthetic tree crown images, each corresponding to a 9.75 m by 9.75 m by area at treetop level, centered on the model tree top. The boundary of the optimal match window is marked in white on each image.



Figure 4. Image "120" with the 171 tree tops as manually marked indicated by circles (1 m radius at treetop level) and the 171 tree top candidates found with the optimal match window indicated by dots.



Figure 5. Image "124" with the 171 tree tops as manually marked indicated by circles (1 m radius at treetop level) and the 171 tree top candidates found with the optimal match window indicated by dots.

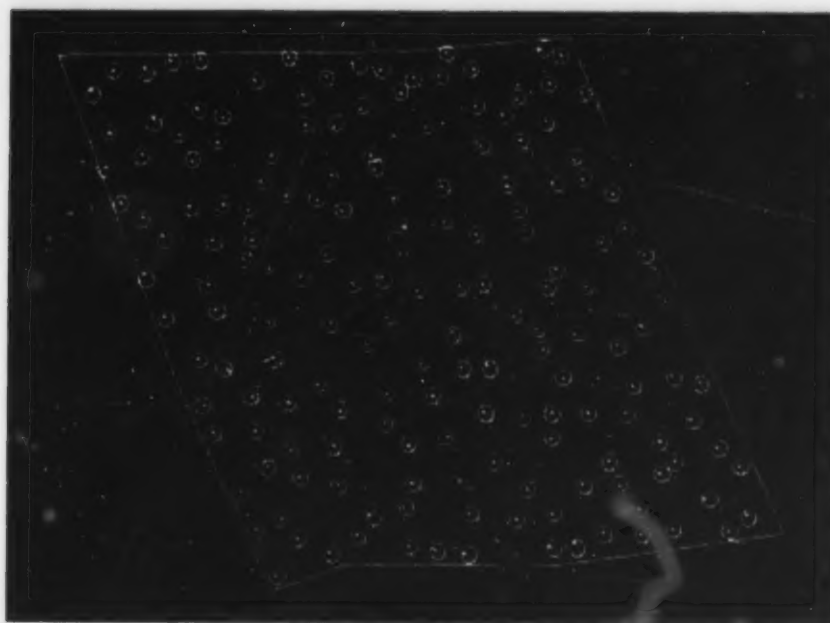


Figure 6. Image "144" with the 171 tree tops as manually marked indicated by circles (1 m radius at treetop level) and the 171 tree top candidates found with the optimal match window indicated by dots.

A SPATIAL CLUSTERING APPROACH TO AUTOMATED TREE CROWN DELINEATION

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ABSTRACT

Forest resource information is increasingly needed at fine spatial scales for use in operational to strategic management programs. Applications include multiple-use management, planning harvesting operations and silvicultural prescriptions, and ensuring the maintenance of biodiversity and ecological sustainability. High resolution remotely sensed imagery is one data source that has demonstrated, and continues to demonstrate, great promise. The benefits of high spatial resolution data include the potential to apply algorithms capable of automatically delineating individual tree crowns in the imagery.

These algorithms commonly search for distinct spectral patterns in the forest scene and use specific image features for the automated delineation of individual tree crowns. These include the spectral maxima and minima, being indicative of crown centroids and boundaries respectively.

This paper describes a threshold-based spatial clustering approach to tree crown delineation. The algorithm is designed for application in Australian native forests, where the dominant genus, *Eucalyptus*, typically exhibits low foliage density and complex crown structure. Algorithm features designed to minimise crown segmentation were therefore key considerations.

The effects of distortions in high resolution imagery is also discussed, particularly those variables that will influence the spectral 'topography' of the forest canopy, notably sun angle and viewing geometry. To achieve this, a 3-Dimensional simulation model has been developed which allows bi-directional reflectance and off-nadir viewing angle effects to be investigated.

Keywords: TIDA (Tree Identification and Delineation Algorithm), tree crown, reflectance, image distortions, forest stand modeling, eucalypt.

RÉSUMÉ

APPROCHE DE REGROUPEMENT SPATIAL POUR LA DÉLIMITATION AUTOMATISÉE DES HOUPPIERS

On a de plus en plus besoin de renseignements sur les ressources forestières, à des résolutions spatiales de plus en plus élevées, qui seront utilisées dans les programmes de gestion opérationnelle ou stratégique. Les applications comprennent la gestion à usage multiple, la planification des opérations d'exploitation et des prescriptions en matière de sylviculture ainsi que le maintien de la biodiversité et de la durabilité écologique. L'imagerie télédéetectée à haute résolution est une source de données qui s'est révélée et continue d'être très prometteuse. Les avantages des données à haute résolution spatiale comprennent la possibilité d'appliquer des algorithmes capables de délimiter automatiquement les houppiers dans l'imagerie.

Ces algorithmes cherchent généralement des configurations spectrales distinctes dans la scène forestière et utilisent des caractéristiques spécifiques de l'image pour circonscrire les houppiers. Ces caractéristiques comprennent les minimums et les maximums spectraux, ces derniers étant respectivement des indicateurs des centres et des limites des houppiers.

Ce mémoire présente la description d'une approche de regroupement spatial basé sur un seuil pour la circonscription des houppiers. L'algorithme est conçu pour des applications dans des forêts naturelles australiennes où l'espèce dominante, l'*Eucalyptus*, présente normalement une faible densité de feuillage et une structure de houppier complexe. Les caractéristiques de l'algorithme conçu pour minimiser la segmentation des houppiers ont par conséquent été des facteurs clés.

On traite également des effets de distorsion dans l'imagerie à haute résolution, notamment les variables qui influent sur la "topographie" spectrale du couvert forestier, particulièrement l'angle solaire et la géométrie de la prise de vue. Pour surmonter ces obstacles, on a mis au point un modèle de simulation tridimensionnel qui permet d'étudier les effets de la réflectance bidirectionnelle et de l'angle de prise de vue latéral.

INTRODUCTION

The need for accurate, timely and cost-effective forest information is essential for sustainable forest management, the conservation of biodiversity, and for providing a greater knowledge of the dynamic processes of forest growth and succession. Understanding these processes will help us to identify criteria and indicators of ecological sustainability, incorporating the environmental, economic and social values of forest management.

These indicators are vital to sound forest management, however, their usefulness must also be judged by our ability to measure and monitor them accurately and efficiently.

Remote sensing is an obvious tool to facilitate the measuring and monitoring process. High spatial resolution remote sensing systems can provide detailed information about forest structure while still covering large areas of forest. Complementary improvements in processing and interpretation techniques may allow us to yield the potential benefits of this data, providing information suitable for integration into a variety of management programs.

The paper explores the development of the Tree Identification and Delineation Algorithm (TIDA), which is designed to automatically delineate tree crowns in high resolution digital imagery. This paper will describe the individual stages of the tree delineation process and the generation of spectral and spatial crown statistics. Specific design criteria will also be discussed, such as the need to minimise crown segmentation. This is particularly relevant to Australia's dominant forest genus, *Eucalyptus*, which typically exhibits low foliage density and complex crown structure, as opposed to the symmetrical and uni-peaked nature of conifers.

A major advantage of tree delineation algorithms for mapping and monitoring forest structure is the potential for consistency and reliability, factors which are essential for successful monitoring and change detection programs. Therefore, specific focus is given to the distortions which commonly occur in remotely sensed imagery, particularly those which may strongly effect the spectral 'topography' of the forest canopy. To investigate these distortions, a 3 Dimensional (3D) model was designed to generate an artificial forest for simulating the effects of changing viewing and illumination positions on TIDA performance. Results from this model and recommendations for future work are also detailed.

AUTOMATED TREE CROWN DELINEATION

Without some kind of spatial structure, an image would resemble random noise, therefore there is important spatial information in all images that are of interest to remote sensing applications (Strahler *et al.*, 1986). Unlike spectral-only classifications, tree delineation in high spatial resolution imagery benefits from this spatial information, as the identification of likely tree crowns can be made on the basis of a formulated *a priori* assessment of how tree crowns respond to incident electromagnetic radiation.

Gougeon (1995) in the description of a valley-following approach to automated tree crown delineation, uses pre-determined rules derived from an assumed interaction between the forest canopy and incident sunlight as the basis of the tree isolation algorithm. Similarly, Fournier *et al.* (1995) showed that recurrent radiometric patterns in forested imagery can be used to successfully discriminate between different forest species at the individual tree level. This awareness of context, or *a priori* knowledge, is often fundamental to the automated interpretation of remotely sensed imagery (Estes *et al.* 1986).

A key component of the canopy-light interaction is the effect of the physical arrangement of trees in a forest stand. Regardless of the spectral or spatial capacity of the remote sensor, usually only a fraction of the total number of trees in a stand will be visible in remotely sensed imagery. This is especially so in mixed-species, multi-aged stands, but may also be the case in even-aged stands.

This variation in crown visibility is principally a function of the competition between individual trees, resulting in the partitioning of crowns into different dominance classes. Thus the structural nature of a forest may appear deceptively simple from above-canopy images, with few of the sub-dominant trees being visible. In mixed-species stands, the presence of species tolerant of low light conditions may also be difficult to detect, usually persisting below the dominant upper canopy.

From a tree delineation perspective, it is apparent that in any but the most homogenous forest canopies, only a fraction of the total number of trees will be discernible in above-canopy imagery. Successful separation of directly sunlit crowns is also a complex issue in natural forest environments with trees often distributed in a clumped or contagious pattern (Payandeh, 1974; Hamilton, 1988). This may result in groups of tightly clustered trees, making the isolation of individual crowns a difficult task.

As a result, the term 'individual tree crown delineation', when interpreted literally, suggests a degree of accuracy that may not be inherent in the delineation process. The term 'canopy object' delineation is likely to be more correct, however, for the purpose of descriptive clarity, we will continue to use the term 'tree crown delineation'.

TREE IDENTIFICATION AND DELINEATION ALGORITHM (TIDA)

High resolution images of a forested environment may be likened to a mountainous landscape (Gougeon 1995), related to the spatial and spectral nature of the image components. The tops of trees appear brightest, being directly illuminated by the sun, while the gaps between trees are darker due primarily to directional reflectance and shading from adjacent crowns. The result is a useful relationship between geometric and radiometric crown shape. Figure 1 shows the actual reflectance of a medium-sized *Eucalyptus* tree crown subset from Digital Multi-Spectral Video (DMSV) imagery acquired near Batemans Bay, in south-eastern Australia (Coops *et al.* 1998). The imagery was collected from a light aircraft at a spatial resolution of 2 m and was post

re-sampled to 1 m. The camera used had a 12mm lens and field of view of 30 degrees. The complete specifications of the camera is given in Pickup *et al.* (1995).

The spectral maxima (peaks) and minima (valleys) are the primary image features used for the identification of crowns, being indicative of crown centroids and boundaries respectively. In TIDA, only one band, usually from the infrared region of the spectrum, is used to perform the tree delineation, although multiple bands are used for initially distinguishing between vegetation and non-vegetation pixels, and for the generation of spectral statistics for each crown following delineation. The distinction between vegetation and non-vegetation pixels is based on a simple parallel-piped classifier. Successful discrimination between vegetation and non-vegetation, and overstorey and understorey will therefore depend on available spectral bands and user-supplied class boundaries.

TIDA uses a 'top-down' approach to tree delineation, which involves the identification of spectral maxima within a local neighbourhood of pixels. These clumps of spectral maxima are then used to calculate the position of 'seeds' around which the rest of the crown is clustered. This process is described below.

FINDING THE SPECTRAL MAXIMA

Distinguishing between true spectral maxima, and maxima indicative of a crown centroid is an important step in the delineation process. TIDA relies on the spatial clustering of adjacent pixels that have been identified as a local maximum for calculating the coordinates of tree crown centroids. The calculated centroids are the starting points (seeds) for the crown delineation process. As a result there will only be as many crowns defined as there are centroids, and therefore the number and position of spectral maxima will have a significant bearing on the outcome of the tree delineation process.

For each pixel in the image, a four-way linear search (horizontally, vertically, and in both 45 degree planes) is performed for numerical peaks, as illustrated in Figure 2. Because image resolution and quality may vary considerably, the distance of this search is user-specified, allowing the user to vary the search distance to (i) overcome small peaks associated with the internal structure of tree crowns that may be visible in very high resolution imagery, or (ii) smooth over extraneous values attributed to random noise. A numerical peak (with respect to TIDA) is considered to exist if the average of the pixels to the left and right of the central pixel is less than the value of the central pixel.

The number of times that each pixel is identified as a spectral peak is recorded. The final value for each pixel will therefore range from 0 - 4, and is indicative of the probability of a given pixel belonging to the spectral peak of a tree crown, with four being the highest probability and zero the lowest.

To draw an analogy, the procedure can be likened to contour lines on a topographic map. If a line is drawn so as to intersect a mountain peak, and the elevation values along the line are plotted, the resulting graph will always reflect a peak in elevation regardless of the direction that the line is drawn. Other topographic features may also display peaks in elevation but will be directionally dependent, for example, a topographic ridge will exhibit peak elevation values in all directions except parallel to the ridge line.

Spatially adjacent pixels that have been identified as maxima and are considered probable crown peaks are clustered. The average reflectance of the pixels in the cluster is calculated (stored as the parameter MAX_AVE) along with the coordinates of the cluster centroid. If the centroid is not inside the cluster, then the coordinates of the nearest cluster pixel are stored instead.

FINDING THE SPECTRAL MINIMA

The spectral minima, or 'valleys', are used to construct a continuous network of absolute crown boundaries of one pixel width between all likely tree crowns. Only pixels within each 'enclosure' defined by the minima may be considered for clustering with the 'seed' inside the enclosure. If there is no seed in the enclosure, which is strongly dependent on user-defined parameters, then no canopy object will be defined.

Similar to the identification of spectral maxima, a four-way linear search is used to locate the spectral minima. However, unlike the maxima, a pixel identified as being a local minimum in any of the four directions is considered valid regardless of directional counts. Minimums are defined as existing when the value of pixels either side of a central pixel increase and then simultaneously decrease. In some cases, it is possible for a pixel to be classified as a minimum in one of the search directions whilst also being identified as a maximum in one or more of the other directions. If such a case arises, minima are always given preference over maxima.

A number of filters are used to refine the identified minima pixels into a clear and continuous network of absolute boundaries. The main processing steps are:

- a) join nearly-linked minimum pixels;
- b) remove small, isolated groups of minimum pixels;
- c) remove minimum pixels that have less than two minimum pixel neighbours;
- d) systematically delete minimum pixels until the remaining network is only one pixel wide.

Figures 3 (a) - (c) compare an original image and identified minima before and after processing respectively. The imagery shown was subset from the DMSV imagery of Batemans Bay and is approximately 100m x 100m. In this case no attempt is made to distinguish between vegetation and non-vegetation pixels.

An important point is that small valleys, albeit true spectral minima, are effectively ignored if they occur within the enclosure of a complete spectral valley. Such an approach restricts the influence of spectral valleys associated with the internal structure of tree crowns on the crown clustering process. Thus spectral minima are only deemed to be absolute boundaries if they belong to the network of continuous minima. This is intended to minimise crown segmentation, particularly evident in very high resolution imagery, and in mixed species uneven-aged forest types that commonly exhibit complex crown structures. It is noted that the use of a low-pass filter may also reduce the crown segmentation problem, however, it is uncertain how the subsequent loss of spatial information in the image will affect overall delineation accuracy.

THE CLUSTERING PROCESS

Once the spectral maxima, absolute crown boundaries, and likely crown centroids have been identified for the entire image, each crown is then delineated individually. The delineation process is initiated by examining the properties of pixels spatially adjacent to a computed crown centroid. The properties of interest are the reflectance (the digital number) of the pixel and whether the pixel is a known boundary pixel.

The parameter MAX_AVE is adjusted by a user-specified value which is used to calculate a threshold for accepting or rejecting a pixels' membership to the crown. Pixels are classified as belonging to a given crown if their reflectance is greater than the computed threshold value, and the pixel is not a boundary pixel.

The process is repeated for all new pixels until no further pixels can be added (meaning pixels adjacent to the crown are either spectrally invalid, or the pixels are crown boundaries). The spatial clustering process is illustrated in Figure 4.

GENERATING CROWN STATISTICS

A number of spectral and spatial statistics can be derived from the delineated crowns for use in modeling tree and stand attributes in conjunction with field data. The use of these statistics is beyond the scope of this paper, however, some key parameters generated by TIDA, and some potential modeling applications are summarised in Table 1.

TIDA also produces a series of images depicting the delineated tree crowns, as well as images of the identified maxima and crown boundaries which may assist the user to optimize input parameters for each image.

THE EFFECT OF IMAGE DISTORTIONS ON TREE DELINEATION

In order to realize the potential benefits offered by automated image interpretation techniques, the algorithms applied must be either capable of accounting for the distortions and variation inherent in remotely sensed data or should provide an indication of the extent of the distortions, so the results can be interpreted accordingly.

Sources of variation in remotely sensed imagery include relief distortion, lens vignetting, atmospheric attenuation, sensor-specific bias, changes in scale and spatial resolution, and notably the effects associated with variation in scene illumination and viewing geometry. It is these last two distortions, specifically the issue of bi-directional reflectance and off-nadir viewing, which will be the focus of the remainder of this paper.

In order to ascertain the effects of changing sun and viewing angles on TIDA performance, a 3D graphical model was developed to permit the simulation of a forest environment according to user-supplied parameters.

The 3D model is similar to a number of previously developed models (Li and Strahler 1985; Li and Strahler 1992; Strahler and Jupp 1990) in that it regards trees within a forest stand as discrete objects approximated by spherical ellipsoids casting shadows on a contrasting background. The model uses parallel ray geometry to describe the illumination of the three dimensional ellipses and the shadows they cast. As the model is used to simulate high resolution remotely sensed imagery, the pixel size is assumed to be smaller than the tree crown, and as a result, pixels are labeled as either sunlit crown, shaded crown, sunlit background or shaded background. The diameter of simulated crowns and their heights above a reference datum are determined by drawing values from a lognormal distribution with sample mean (μ) and standard deviation (σ). Their dispersal across the landscape follows a random Poisson process (Li and Strahler 1985; Strahler and Jupp 1990; Kuuluvainen and Pukkala 1989) based on a specified mean occurrence of trees per unit area. The only constraint to placement being a maximum allowable overlap between crowns.

A simple illumination model is applied to the ellipsoids based on the angle of divergence between the surface normal and the source of illumination. Background that is unobscured by objects or their shadow is similarly illuminated using this model. Illumination coefficients allow for variable intensities of direct and ambient light, and for varying degrees of surface reflectivity. The scene is viewed from a specified height above the ground through a projection plane of variable height and horizontal dimensions. The position of the viewing point and projection plane relative to the ground and the dimensions of the projection plane determine the extent of off-nadir viewing and the spatial resolution of the resulting image. Figure 5 gives an example of the arrangement and shape of some simulated trees.

SPECIFICATIONS OF SIMULATED IMAGERY

Two sets of simulations were used to investigate the effects of changes in viewing geometry and sun angle. A variable viewing angle dataset was created by maintaining a constant illumination point (directly above the image principal point) while systematically reducing the viewing height. Similarly, for the sun angle dataset, the viewing position remained constant while the sun angle was incremented. A simulated forest scene was created each time the viewing or illumination position changed.

Both sets of imagery were generated to achieve a ground spatial resolution of 1 metre. Trees were created with an average crown radius of 5 m and standard deviation of 1.5 m. A maximum crown overlap of 35% was applied. A density of 400 stems per hectare was initially selected, however due to constraints on crown overlap, the final stand density was allowed to decrease to 100 stems per hectare.

Each image was simulated for a forest stand of 500 m x 500 m resulting in 2549 and 2599 trees being allocated for the viewing angle and sun angle simulations respectively. Because TIDA does not consider trees for delineation that lie adjacent to the scene boundary, all trees bordering the image were removed from the initial allocation resulting in 2248 and 2285 trees available for delineation respectively.

Viewing Angle Simulations

Viewing angle varies consistently over an image, from zero degrees at the image principal point to a maximum at the corner extremities of the image, referred to as 'maximum off-nadir'. Maximum off-nadir viewing angle is determined from the image acquisition height and sensor field of view (FOV). Fourteen images were created for simulating viewing positions ranging from maximum off-nadir viewing angles of 2° to 75° respectively. TIDA was run on each of these images and the number of trees identified and their average crown area was recorded.

Sun Angle Simulations

Eleven separate images were created for the sun angle comparison. The illumination position was determined for each scene based on the scene location (latitude/longitude), the time of year and time of day. A latitude of zero degrees was selected in order to maximize variation in sun angle. Similarly, the date chosen for the sun angle calculation was March 21, which is the Autumn equinox when the sun is directly over the equator. The arc of the sun thus passed through a solar elevation angle of 88 degrees at midday.

Local time was increased in hourly increments from 07:00 hours to 17:00 hours (solar altitude angles of 13.4 degrees and 16.9 degrees respectively). The viewing position was maintained at 10 000 metres above the image principal point, the assumption being that viewing angle effects on tree delineation are negligible at this height.

RESULTS AND DISCUSSION

To test the effect of the crown overlap constraint on the spatial distribution of the trees, a ratio of location-to-point distances to point-to-point distances was computed ($n = 2500$). The ratio value (C) is expected to approximate 1 in true Poisson process patterns (Getis and Boots 1978). When the crown overlap constraint is set to 35%, $C = 0.33$, indicating an even point distribution, which may be considered typical of the arrangement of upper canopy or 'visible' tree crowns. Without the crown overlap constraint, $C = 0.99$ suggesting that the placement of the trees by the model is consistent with a Poisson point distribution. As noted, however, tree crowns visible to above-canopy viewing, and which have the highest likelihood of automated delineation, will have a regular point pattern when the overlap constraint between neighbouring crowns is applied.

The results of the 14 viewing angle simulations are given in Figure 6. The maximum number of trees identified by TIDA was 2074 (92% of total) at a maximum off-nadir viewing angle of 2 degrees. The average area of the crowns delineated was 61 m², compared with 67 m² for the average area of the simulated crowns.

The effects of changing illumination position on TIDA performance are shown in Figure 7. Optimum crown delineation was achieved at midday when 2019 (88%) of the total number of trees were identified by TIDA. The average area of the delineated crowns was 81 m², while the average area of the simulated crowns was 64 m².

Figures 6 and 7 clearly show the significant effect that variation in viewing and illumination angles can have on the automated delineation of tree crowns in high resolution imagery. The results are concurrent with the expectation that the most reliable tree delineation occurs at high solar elevations and small off-nadir viewing angles.

Figure 6 suggests that automated tree delineation in imagery with off-nadir viewing of greater than 40 degrees may yield unreliable results. Improvements in camera instrumentation and flight planning techniques means that the acquisition of imagery at these angles is rarely necessary and high resolution satellite data in particular will be largely devoid of such distortion. The issue of appropriate viewing angles will arise, however, in monitoring programs aimed at detecting changes in the forest ecosystem over a given time interval. If the principal points of imagery acquired from one date to the next do not coincide, then apparent changes in forest structure may in fact be attributed to a change in viewing angle.

Figure 7 indicates that sun angle has the greatest overall effect on tree delineation reliability, although it is uncertain how sensitive these results are to changes in the light intensity and surface reflectivity coefficients used in the illumination model, and the shape of the simulated crowns with respect to between-tree shading (Kuuluvainen and Pukkala 1989). A broad conclusion is that acquisition of imagery before 11 am or after 1 pm local time (in this case a solar elevation less than 70 degrees) will produce unreliable results in terms of the number and average area of crowns delineated. While this may be an intuitive conclusion, it is also likely to pose practical problems, especially at latitudes close to the poles where the solar elevation may remain low for many months of the year.

Simulating variation in sun angle and viewing geometry on imagery of a forested landscape has allowed us to make judgments about the effect of this variation on the reliability and consistency of automated tree crown delineation. Results indicate that changes in these two variables will alter the apparent position and/or visible reflectance of the crown surface, and thus change the spectral 'topography' of the image. The sensitivity of TIDA to changes in the spectral topography of the image is not unexpected, with the process being highly dependent on the nature and position of spectral maxima and minima. It is apparent, though, that in its current state of development, TIDA cannot provide consistent results under variable viewing and illumination conditions.

While beyond the scope of this paper, a future research path will include the combined effects of variation in viewing and illumination positions on TIDA performance. However, it is expected that the outcome of such a trial would not be dissimilar to that undertaken here, i.e., the results would favour image acquisition at high solar angles, and small viewing angles.

A key outcome of these simulations is the requirement for an automated tree delineation algorithm to compute the angle of divergence between viewing and illumination positions for each point in an image, and to modify its approach to the delineation of crowns accordingly. To achieve consistent and accurate tree crown delineation over widely varying viewing and illumination angles is to address one of the primary impediments to the operational application of the TIDA algorithm to long-term monitoring and mapping operations.

CONCLUSION

Some of the main benefits of algorithms such as TIDA lie in their potential to provide consistent, accurate and detailed spectral and spatial statistics of individual tree crowns. This information can then be used to model tree and stand attributes and form the basis of long term mapping and monitoring programs of the forest ecosystem.

Before these techniques can be confidently applied, however, automated interpretation algorithms need to take into account the extent and nature of variation in the source data and anticipate the likely effects this will have on results. We have demonstrated in this paper that TIDA cannot provide consistent results under variable illumination and viewing conditions.

The challenge is to develop a tree delineation algorithm that can account for the most significant sources of variation in remotely sensed data. This is an important step as we seek to promote the use of this technology in an operational environment, and as we demonstrate the numerous benefits in terms of more accurate and reliable resource information, leading to more informed decision making, and ultimately sound and sustainable forest management.

ACKNOWLEDGEMENTS

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Table 1. TIDA parameters and possible modeling applications.

Parameters computed by TIDA	Modeling Application
crown centroids coordinates	spatial distribution of trees or combine with specific parameters for estimating spatial autocorrelations within a stand
crown areas	stem diameters, tree heights, growth stage
irregularity of crown boundaries*	growth stage, species mapping
average distance between neighbouring tree	spatial distribution, site utilization, inter-competition
average within crown spectral reflectance	species mapping, growth stage

*ratio between crown perimeters length and square root, see Feder(1988), p. 200.

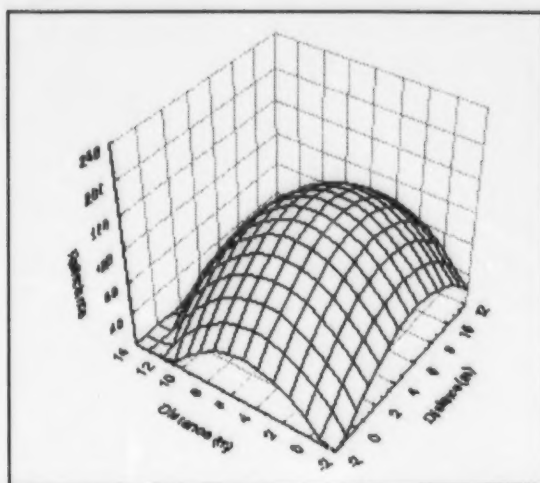


Figure 1. Tree crown subset from DMSV imagery (green band).

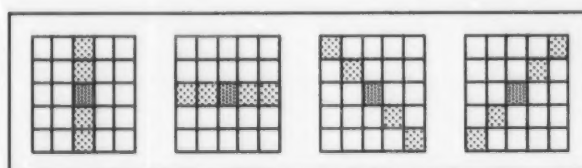
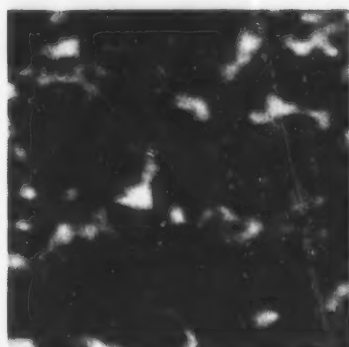
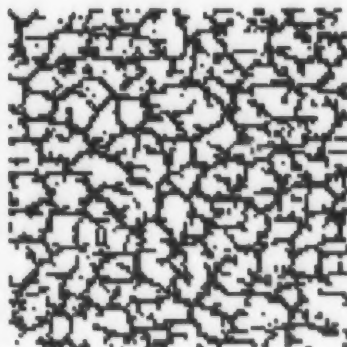


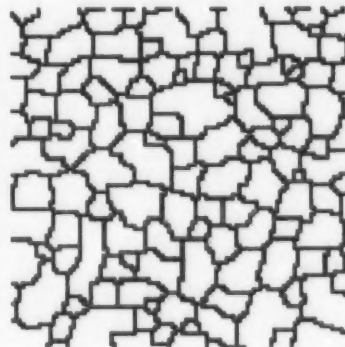
Figure 2. Four-way search for spectral peaks.



(a) Original image



(b) Unprocessed minima



(c) Processed minima

Figure 3. DMSV imagery before and after processing identified minima.

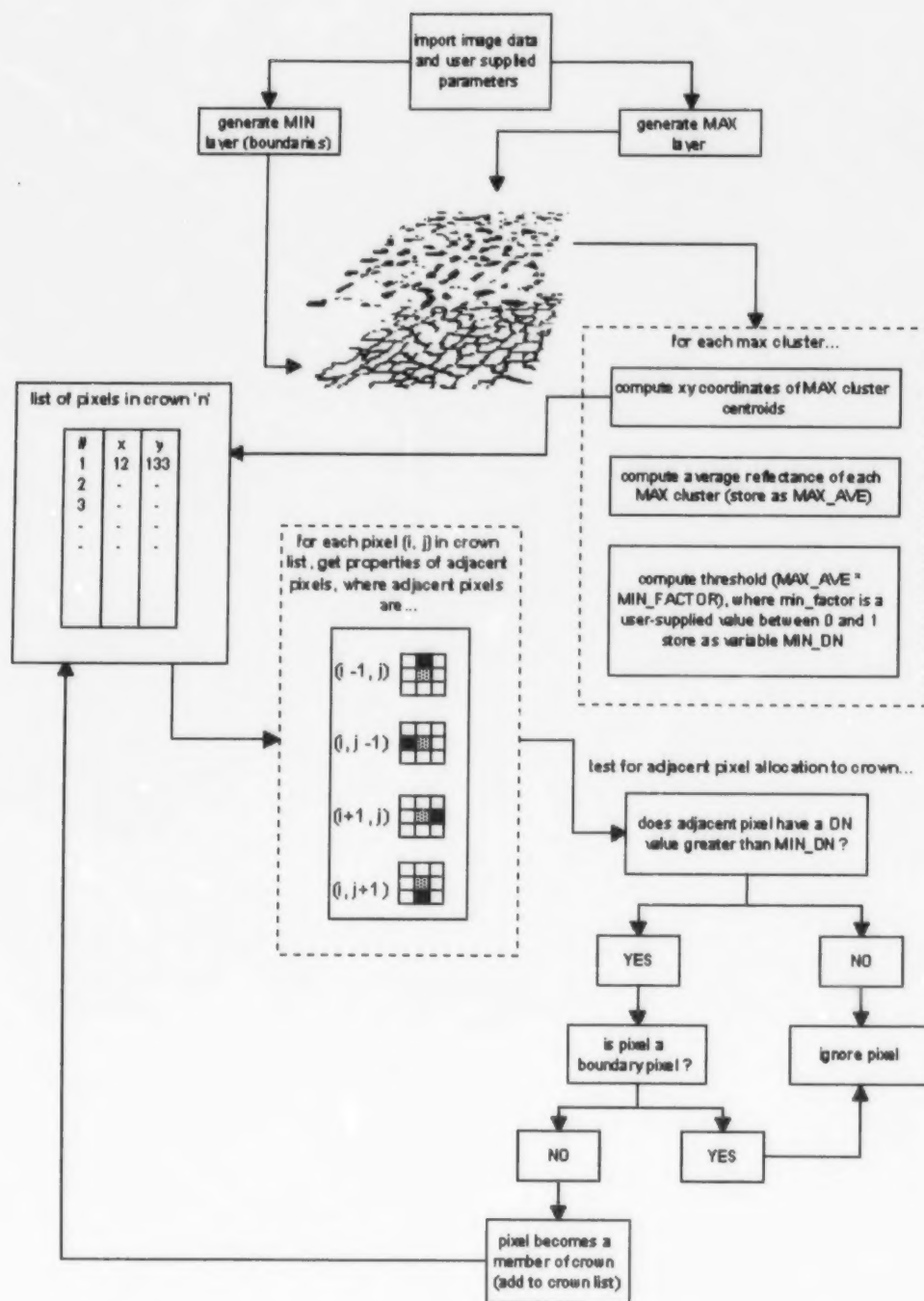


Figure 4. The crown delineation and clustering process.

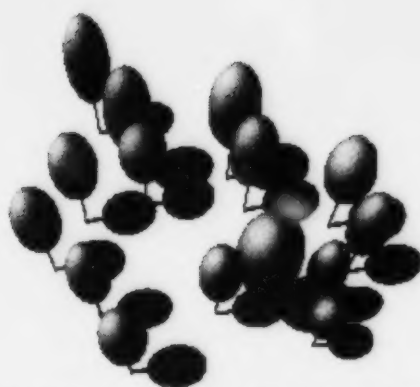


Figure 5. Example of simulated crowns (magnified subset).

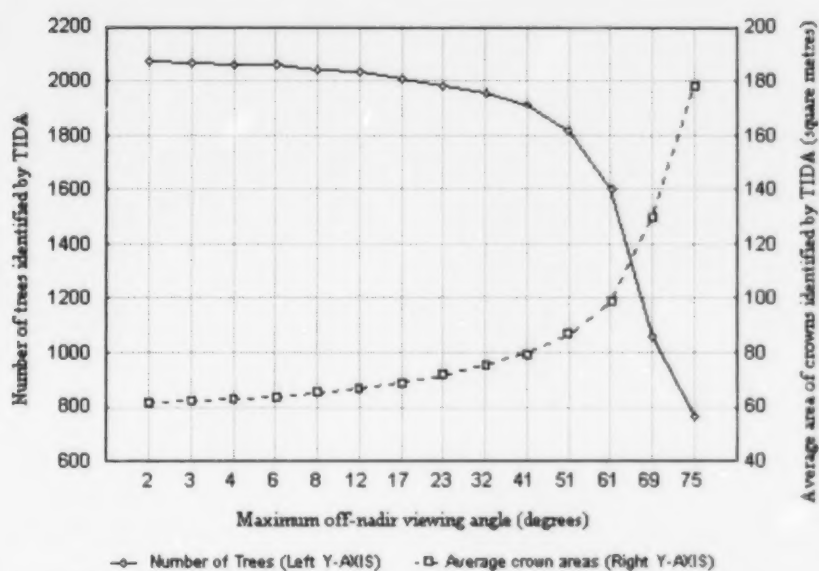


Figure 6. Effect of simulated change in viewing angle on the number and size of tree delineated by TIDA.

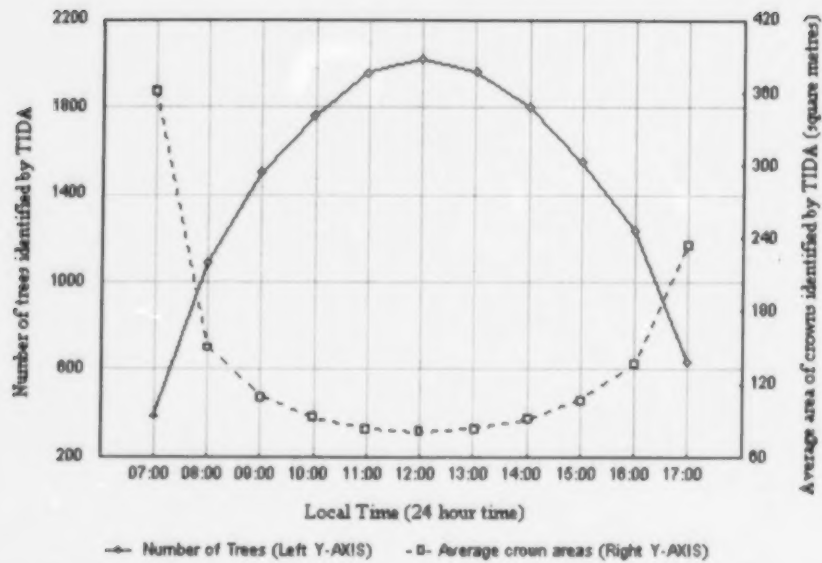


Figure 7. Effect of simulated change in sun angle on the number and size of trees delineated by TIDA..

DELINEATION AND IDENTIFICATION OF INDIVIDUAL TREES IN THE EASTERN DECIDUOUS FOREST

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ABSTRACT

The Ecological Evaluation using Remote Sensing (EERS) group at West Virginia University is studying the health and status of West Virginia's forests using high spatial resolution imagery. Central to our work is a focus on classification and mapping of trees. This paper reports on our initial findings regarding the delineation of individual trees, and discusses future directions we hope to pursue. In a separate paper (Key *et al.* in this volume) we discuss tree species classification using multi-temporal imagery.

Delineation of individual trees in the Eastern Deciduous Forest is challenging due to the variety of scales of tree canopy size, the relatively flat topography of the canopy, and the complex mosaic of the individual crowns. Nevertheless, the shadows between crowns provide a good first cut for identifying tree boundaries. A rank normalization is required to reduce problems due to variable illumination and vignetting. The size of the moving window used in this normalization is crucial in determining the scale of shadows that are enhanced. A window approximately the size of the average tree tends to enhance branching within the crown, whereas a window approximately three times the size of the average tree enhances individual tree crowns. The shadows are, however, in short, separate segments that do not isolate the trees. These segments can be connected by orientation information obtained from a direction of minimum texture algorithm. For each pixel in the image, texture is calculated over narrow groups of pixels (1 pixel wide by 11 long) centered on the pixel of interest. The orientation of these groups is incremented by a small angle until all directions have been tested. The direction with the lowest texture is written out to a new file. A rule-based algorithm is currently being developed to use this information to join shadow segments.

Keywords: tree-boundary, texture, image segmentation, shadows, rank-normalization, texture direction, adaptive filters.

RÉSUMÉ

DÉLIMITATION ET IDENTIFICATION DES ARBRES DANS LES FORÊTS DÉCIDUES DE L'EST DE L'AMÉRIQUE DU NORD

Le groupe sur l'évaluation écologique au moyen de la télédétection (EERS pour Ecological Evaluation using Remote Sensing) de la West Virginia University étudie l'état de santé et la situation générale des forêts de la Virginie-Occidentale à l'aide de l'imagerie spatiale à haute résolution. Les travaux du groupe portent essentiellement sur la classification et la cartographie des arbres. Le présent mémoire fait état des premiers

résultats portant sur la délimitation des arbres et aborde divers aspects que le groupe compte approfondir. Dans un document distinct (Key et coll., dans ce mémoire), le groupe traite de la classification des espèces d'arbres à l'aide de l'imagerie multitemporelle.

La délimitation des arbres dans les forêts décidues de l'est de l'Amérique du Nord pose des défis en raison de la variété des échelles dans les superficies du couvert, de la topographie relativement plane du couvert et de la mosaïque des houppiers. Néanmoins, les ombres entre les houppiers constituent un premier élément d'importance pour identifier les limites de chaque arbre. Il faut procéder à une normalisation du classement pour réduire les problèmes causés par l'éclairement variable et le vignettage. La dimension de la fenêtre mobile utilisée dans cette normalisation est essentielle pour permettre d'établir l'échelle des ombres qui sont accentuées. Dans une fenêtre dont la dimension approximative correspond à un arbre moyen, les branches sont accentuées par rapport au houppier. Par contre, dans une fenêtre dont la dimension approximative correspond à environ trois fois celle d'un arbre moyen, ce sont les houppiers qui sont accentués. Toutefois, les ombres constituent des segments distincts qui n'isolent pas les arbres. Ces segments peuvent être connectés au moyen de données d'information obtenues par un algorithme de direction de texture minimale. Pour chaque pixel de l'image, on calcule la texture dans des groupes rapprochés de pixels (1 pixel de large sur 11 pixels de long) centrés sur un pixel repère. L'orientation de ces groupes est incrémentée d'un angle étroit, jusqu'à ce que toutes les directions aient été testées. La direction présentant la plus faible texture est transférée dans un nouveau fichier. Un algorithme basé sur des règles est en cours de développement pour pouvoir utiliser cette information en vue de joindre les segments d'ombre.

INTRODUCTION

Ecologists interested in forest dynamics at the individual tree level are only now beginning to explore the potential uses of high spatial and high spectral resolution remote sensing. However, initial attempts to use such data illustrate the potential. For example, Schlesinger and Gramenopoulos (1996) used high spatial resolution aerial photographic and defense satellite data to test for desertification in the Sahel by examining tree densities in images collected over 51 years. This example is particularly illuminating because it shows that not only is satellite remote sensing capable of examining individual trees, using these data it is possible to test for *change* in densities over time. In this study, no time-trend was observed, suggesting that if it is occurring at all, desertification is slower than previously thought in the Sahel (Rapp 1976, Holcombe 1987, El Moghraby 1987). Of course, an equivalent study could have been carried out on the ground, however, sampling interval, area and sample size would have been limited by practical considerations.

A range of ecological problems become tractable with the possibility of locating and identifying individual trees by remote sensing. At one end of the spectrum is the detection of rare individuals, genotypes, or species. Detection of rare elements in a forest community is important in several kinds of ecological studies. A forest pathologist may have a particular interest in detecting the presence of rare survivors of a disease or insect pest outbreak in order to find resistant individuals. For example, in the eastern deciduous forest field ecologists have observed occasional large American chestnut individuals that have reached reproductive size and age despite exposure to ubiquitous chestnut blight. It may be that 99% of such cases are due to chance escape from the blight, but 1% are due to genetically based resistance. Detection of a large enough sample of reproductive chestnuts to perform genetic screening could be impossible without an extensive search procedure such as that provided by remote sensing.

At the opposite end of the spectrum is the location and identification of individual trees of a common species in a diverse community of similar species. Here, the interest shifts from one of detection of a rare type to defining the individual tree and making relevant measurements on it. The interest may also shift from one of detection to one of examining change over time, both change in individuals (measuring their size changes, detecting their death, assessing their 'health') and in populations (recruitment of new individuals).

In general, assessing attributes that change over time poses the greater technical challenges, however the potential benefits make addressing these challenges worthwhile. One application of multi-temporal remote sensing with excellent payoffs is large-scale population modeling. Minimally, parameterization of a population

matrix model of a forest tree species requires repeated censuses of individual trees, including accurate (a) delineation of individuals from the community, (b) classification of individuals to species, (c) size determination, (d) determination of whether an individual is dead or alive at a given point in time, and (e) matching of individual trees across census intervals. All of these steps present some technical challenges for raw data acquisition, image registration and image processing. Even when these challenges have been met, biological assumptions about size-dependent recruitment will be required. Sampling the forest canopy on a 5-year (± 2 year) time frame and sampling at the highest possible spatial resolution will help ensure that calculated size transition probabilities and mortality accurately represent the true population changes occurring. Ultimately, the goal of a remote sensing - population modeling marriage would be to assess region-wide status of forest-tree populations on the order of 10^6 - 10^7 trees. From this, it should be possible to overlay demographic patterns and environmental data in a comprehensive GIS database that will provide resource managers with the information needed to judge forest health and the consequences of alternative management strategies.

The Ecological Evaluation using Remote Sensing (EERS) group at West Virginia University is developing the tools to make such studies possible. Central to this work is a focus on classification and mapping of trees. This paper reports on our initial findings regarding the delineation of individual trees and discusses the direction we hope to pursue in future work. In a separate paper (Key *et al.* in this volume) we discuss the value of spectral information versus temporal information in classification of tree species.

IMAGE SEGMENTATION

For our eye-brain vision, the spatial properties of context, pattern and texture are almost certainly a great deal more significant than the spectral property of color. It is therefore intriguing that spatial properties are so rarely drawn upon in remote sensing image analysis. In fact, most image analysis techniques are based on aspatial statistical methods. Nevertheless, the individual tree delineation applications discussed in the previous section clearly require an explicitly spatial approach to image analysis. Image segmentation can be one way of incorporating spatial information, especially if it is carried out prior to classification. In this case, each segment can be classified as a single unit, thus simultaneously enhancing the overall accuracy and reducing the number of classification decisions made, thus reducing classification time (Kettig and Landgrebe, 1976). Segmentation can be purely spectral in nature, such as the ECHO algorithm in which groups of adjacent pixels are tested for spectral homogeneity (Kettig and Landgrebe, 1976). Alternatively, spatial information can be incorporated in the segmentation through attributes such as texture (Ryherd and Woodcock, 1996).

One of the main problems with image segmentation is that there are normally a number of scales in a scene (Woodcock and Strahler, 1987; Strahler *et al.*, 1986). This makes it hard to define definite spatial rules to separate classes. Furthermore, the within class variability of the classes can be greater than the between-class variability. Yet another problem is that if spectral properties are used in image classification, the small number of samples involved make it difficult to exploit class covariance information. This is significant because when there are five or more bands present, much of the class-separability probably derives from differences in class covariance, rather than separation of class means (Lee and Landgrebe, 1993).

Segmentation of individual trees has its own distinct opportunities and problems. In coniferous stands, the tops of the trees are typically the brightest pixels in high spatial resolution images (Gougeon, 1997a). Because of the conical shape of conifers, the bordering shadows are particularly useful in image segmentation. If an image has deep shadows, a threshold can sometimes be applied to separate out the bright pixels as individual trees. Gougeon (1995) has used a rule-based approach for automated tree outline delineation exploiting the local "valleys" of local radiance minima that surround each tree. If trees are further apart, and the ground is illuminated, tree shadow direction can be used to identify structural properties such as stand density (Gougeon, 1997b; St-Onge and Cavayas, 1997).

Our study area is in the Eastern Deciduous Forest of North America. This forest is very different from the coniferous forests where tree segmentation has been so successful. Firstly, the canopy tends to form a complex mosaic as individual trees exploit available canopy gaps. In some cases we have found branches of different

trees intertwined, making delineation of the canopy extent of trees very complex. Furthermore, the size and spacing of trees can be very variable, limiting the spatial properties of size and frequency that can be exploited.

Despite the highly efficient exploitation of canopy gaps, we have found a general tendency for trees to be surrounded by narrow bands of shadow. Unfortunately, however, there are also shadows between the major branches, and in many cases these branches occupy areas of the canopy greater than that of the smaller individual trees. Furthermore, the edges of these shadows tend to be diffuse, and the shadows themselves are not continuous. Although some deciduous species do have a distinct profile, the canopy of the mature Eastern Deciduous Forest tends to be relatively uniform in elevation without the marked variation in height that has proved so useful in the West. Old growth forests are much more structurally diverse, but are relatively rare in these forests. These factors make standard edge detection methods, and general rules about the size and shape of trees, of questionable value.

DATA

Our study site is located in the West Virginia University Forest, a 3,509 hectare research facility on Chestnut Ridge, 15 kilometers east of Morgantown, West Virginia. The Forest lies at an elevation 318-795 meters and is dominated by a diverse mixed mesophytic forest. The site is 100 by 100 meters in size and has been mapped from the ground in great detail. Each tree has been identified, its position surveyed, and the bole size (DBH) and canopy diameter measured. Yellow poplar (*Liriodendron tulipifera*) is the most common species, comprising a little over 50% of the plot. Subsidiary species include red and white oak (*Quercus rubra* and *Q. alba*) and red maple (*Acer rubrum*).

The site has also been photographed 10 times from the air over the spring, summer and fall of 1997. The photography was acquired with two Nikon 35 mm cameras with color and color and color-infrared film. The photographs were scanned using a flat bed scanner, and then individually geometrically co-registered and, if necessary, mosaicked. The base for this geocoding was a photograph acquired with a large format mapping camera, which has excellent photogrammetric qualities. The nominal pixel size of the co-registered images is 6 centimeters. Although the effective resolution of the images is somewhat coarser, this high resolution provided a method for ensuring the maximum quality in co-registration of the images. Furthermore, for the texture analysis discussed below, the smaller pixel size facilitates a fine resolution of texture angles.

For this paper only the color photography from October 23, 1997 was used. This date was chosen because it combines good spectral separability of the major species, with a moderate sun angle and distinct shadowing around many of the trees. (See Figure 1.)

METHODS AND RESULTS

INITIAL BOUNDARY IDENTIFICATION FROM SHADOW THRESHOLDING

The simplest method of identifying the boundaries of the canopy of individual trees is from the shadows on the periphery of each tree. A single band was created from the three visible bands of the rectified photograph for this analysis of shadows. This new band is termed an illumination/albedo image in that it combines both illumination and overall reflectance variations in the three bands. The illumination/albedo band is produced by calculating the magnitude of the vector represented by the spectral value of each pixel, after the haze component has been removed (Pouch and Campagna, 1990). This is achieved by taking the square root of the sum of the squares of the bands.

The resulting image (Figure 1) has the variations in brightness typical of imagery acquired with devices with a large field of view, and especially non-mapping cameras. Therefore, no one threshold can be applied to this image to isolate shadows over the scene as a whole. Fortunately, this problem can be overcome through a standard procedure of normalizing pixels within a matrix of pixels defined by a moving window. In our case we used a rank normalization. In this procedure the rank of the central pixel, with respect to the pixels in the

local window, is returned to the output image. Special procedures have to be applied to deal with pixels on the edges of the image, where the rank is adjusted to take into account the smaller number of pixels in the window.

As a spatial operation, the size of the window relative to the scale of the image objects is crucial in this analysis. For example, a 101 by 101 matrix (approximately 6 meters by 6 meters) is approximately the size of a single tree. Thus, the normalization at this scale is very effective at enhancing the individual branches that make up a tree. A larger window size of 301 by 301 (approximately 18 meters by 18 meters) incorporates several trees in each matrix and thus tends to enhance the more significant shadows associated with the boundaries between trees (Figure 2). This window size is great enough to span canopy gaps from dead trees. Larger windows are greater than the scale of the illumination variations in the image and therefore are less effective at suppressing this problem. A cutoff of rank 6,400 (out of the 90,601 pixels in the 301 by 301 window) was selected as the threshold for the discrimination of shadows in this image (Figure 3). This value was chosen as it gave the best tradeoff of identifying many between-tree shadows, with relatively few between-branch shadows (Figure 4). This image was then converted to a binary file for application to the texture image discussed below.

DIRECTION OF MINIMUM TEXTURE

A major problem with texture analyses is that large window sizes are needed to encompass the broad scale of most spatial phenomena. Unfortunately, such large window sizes tend to have a coarsening effect on the image. Furthermore, large window sizes tend to confuse between and within class texture. Ryherd and Woodcock (1996) used an adaptive filter to overcome this problem. Their procedure is to assign the pixel of interest the lowest of the textures of all the windows that incorporate the pixel of interest. This is in contrast to the typical texture analysis, in which the parameter associated with the window centered over that pixel is automatically used. The assumption with the adaptive filter is that the minimum texture associated with that pixel provides the best estimate of this property. Texture derived with an adaptive filter proved useful in image segmentation, although unfortunately the results tend to be somewhat blocky (Ryherd and Woodcock, 1996).

The direction of minimum texture is an extension of the concept of an adaptive filter. However, as will be shown below, it provides additional information relating to the *orientation* of the texture. The texture used for this analysis is the local variance. The direction of minimum texture is based on a comparison of texture in numerous narrow groups of pixels centered on the class of interest. At set angular increments, a linear arrangement of neighboring pixels is chosen from within a larger group of pixels in a square matrix, by setting the matrix positions that define the angle of interest to a value of one. All other matrix positions are given a value of zero, indicating those pixels are not used in the texture calculation. Figure 5 illustrates three (0° , 22.5° and 45°) of the eight angles that can be obtained with a five by five matrix. Larger kernels allow finer resolution of angular direction. In this study an 11 by 11 matrix was used, identifying texture at a scale of approximately 66 centimeters (11 pixels, each of 6 centimeters). The resulting angles are 9° apart, giving a total of 20 directions. Unlike most texture studies, the magnitude of the texture is not of direct interest in this case. Instead we focus on the orientation of the texture as determined by the direction associated with the minimum texture. This attribute is aligned with subtle linear features such as the boundaries of the canopies of individual trees. When the direction of minimum texture information for the entire image is viewed, very little pattern is evident. However, when only the data from the shadow areas is examined, the trends of the shadows can be identified. Figure 6 shows an enlargement of part of the results for the area covered in Figures 1-4. Each color represents a different angle, as indicated by the color wheel below the figure. The manually digitized outlines of the trees have been overlain on the figure to illustrate how this method can be used to identify the boundaries of the trees. The texture orientation of the shadows allows a linking between isolated shadow segments that potentially can be joined to circumscribe each tree. Most isolated noise can be eliminated because the shadows do not have aligned texture orientation. In only a few cases will shadows between larger branches cause incorrect identification of tree boundaries.

CONCLUSIONS AND FUTURE RESEARCH

The delineation of individual trees in the Eastern Deciduous Forest is particularly challenging due to the relatively flat topography of the mature forest canopy and the complex shape of the mosaic of individual

crowns. Nevertheless, shadows identified from rank-normalized images provide an excellent first cut method for identifying the boundaries of trees. The size of the window used in image analysis is crucial in determining the scale of the objects identified. A window size of at least three times the size of the average tree appears to be necessary to ensure that branching is not enhanced at the expense of the discrimination of individual trees.

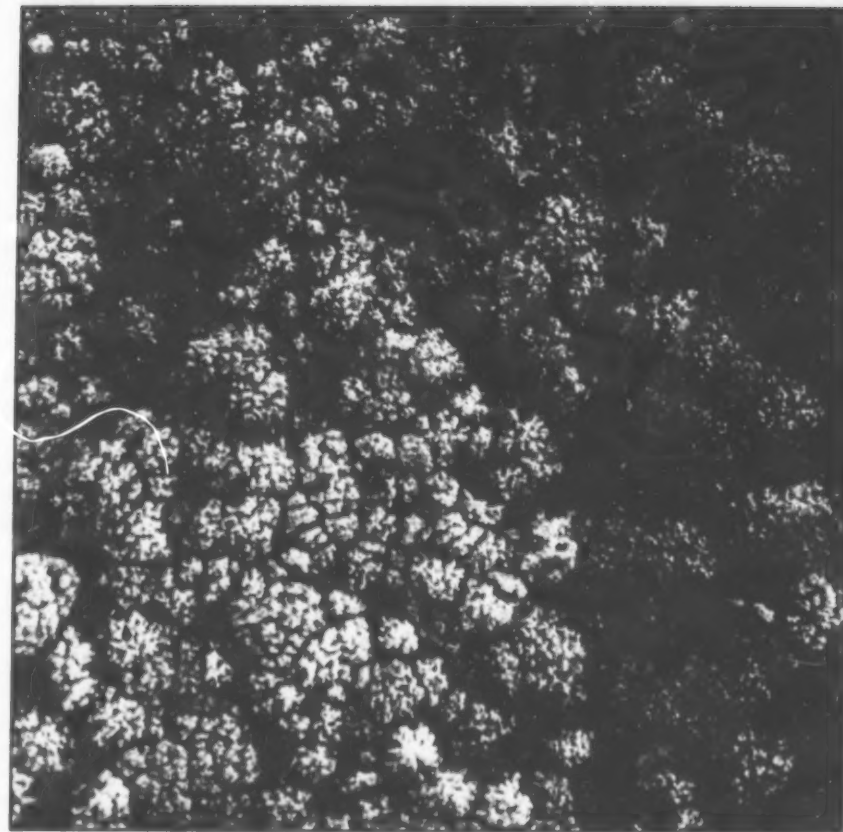
The direction of minimum texture provides additional information that can be used to connect the isolated segments of the shadows. Such information is important, because the individual crowns are not completely isolated by the shadow analysis procedure. We are currently developing a rule-based method to exploit this information. Individual clumps of adjacent pixels with similar minimum texture directions are grouped, and connected to adjoining clumps or projected to nearby clumps. The potential distance of the projection across non-shadow area is dependent on the length and width of the clump, as well as the degree to which this projection is supported by the direction of minimum texture in the intervening non-shadow region.

In future research we plan to incorporate spectral segmentation in our analysis. In highly diverse forests, many trees can be separated based on spectral differences. It therefore would be appropriate to apply tree segmentation in a sequential, or even iterative fashion, in which a variety of boundary detection methods are incorporated in a single tree segmentation program.

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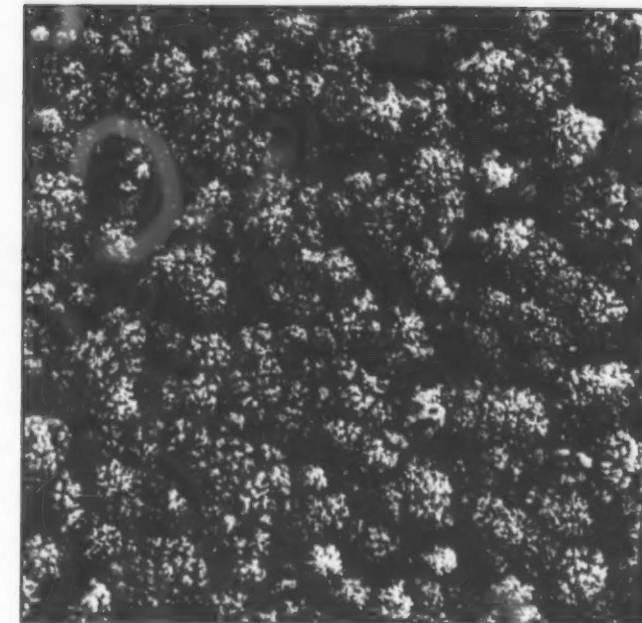
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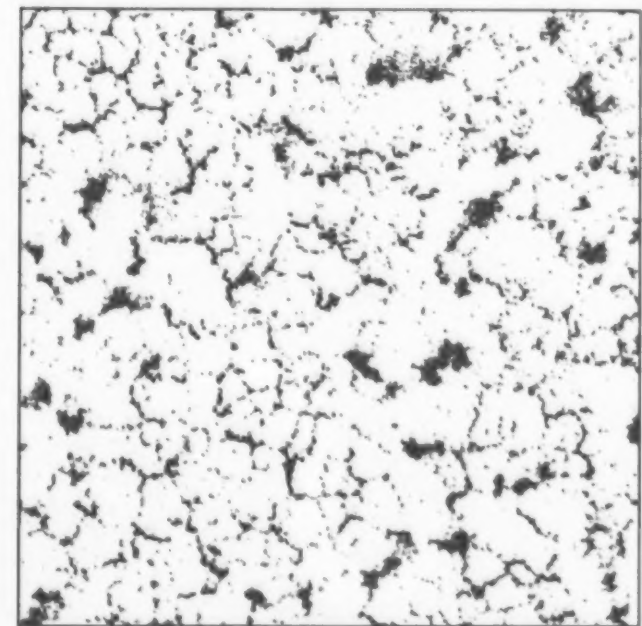
Scale
20 0 20 40 60 Meters

Figure 1. Illumination / Albedo image.



Scale
20 0 20 40 60 Meters

Figure 2. Rank normalized image based on 301 by 301 window.



Scale
20 0 20 40 60 Meters

Figure 3. Tree shadows from rank normalized image.

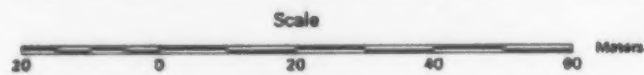
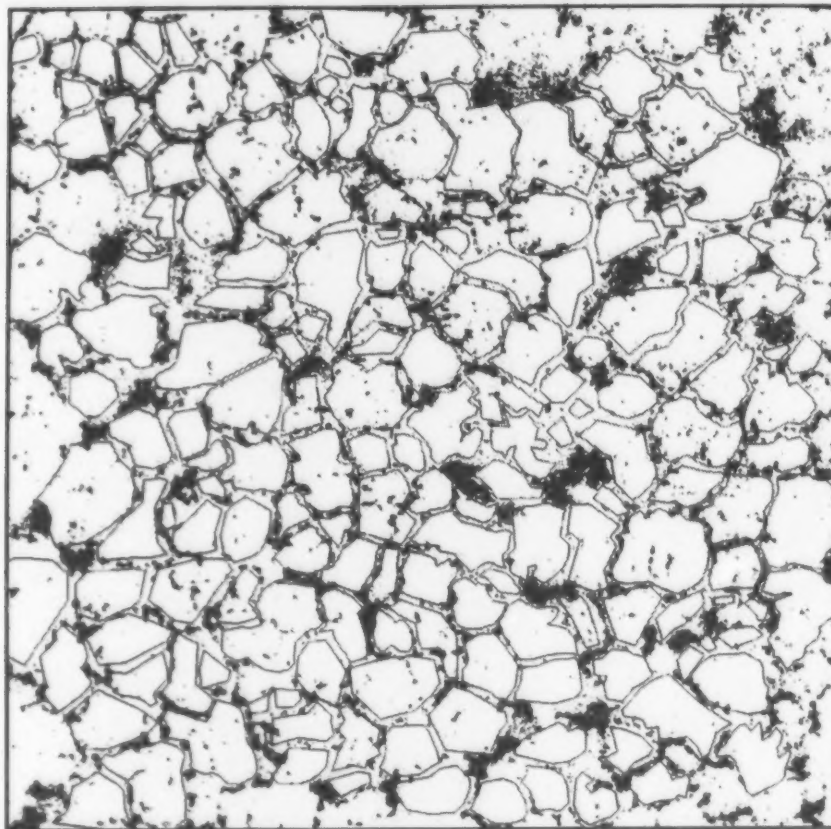


Figure 4. Tree shadows and manually digitized tree boundaries.

0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0

0° Directional kernel

0	0	0	1	0
0	0	0	1	0
0	0	1	0	0
0	1	0	0	0
0	1	0	0	0

22.5° Directional kernel

0	0	0	0	1
0	0	0	1	0
0	0	1	0	0
0	1	0	0	0
1	0	0	0	0

45° Directional kernel

Figure 5. Directional filters are created by filling a matrix with 0 values in all positions, except along the particular angle which is to be investigated. Larger matrix sizes allow finer gradations in angles.

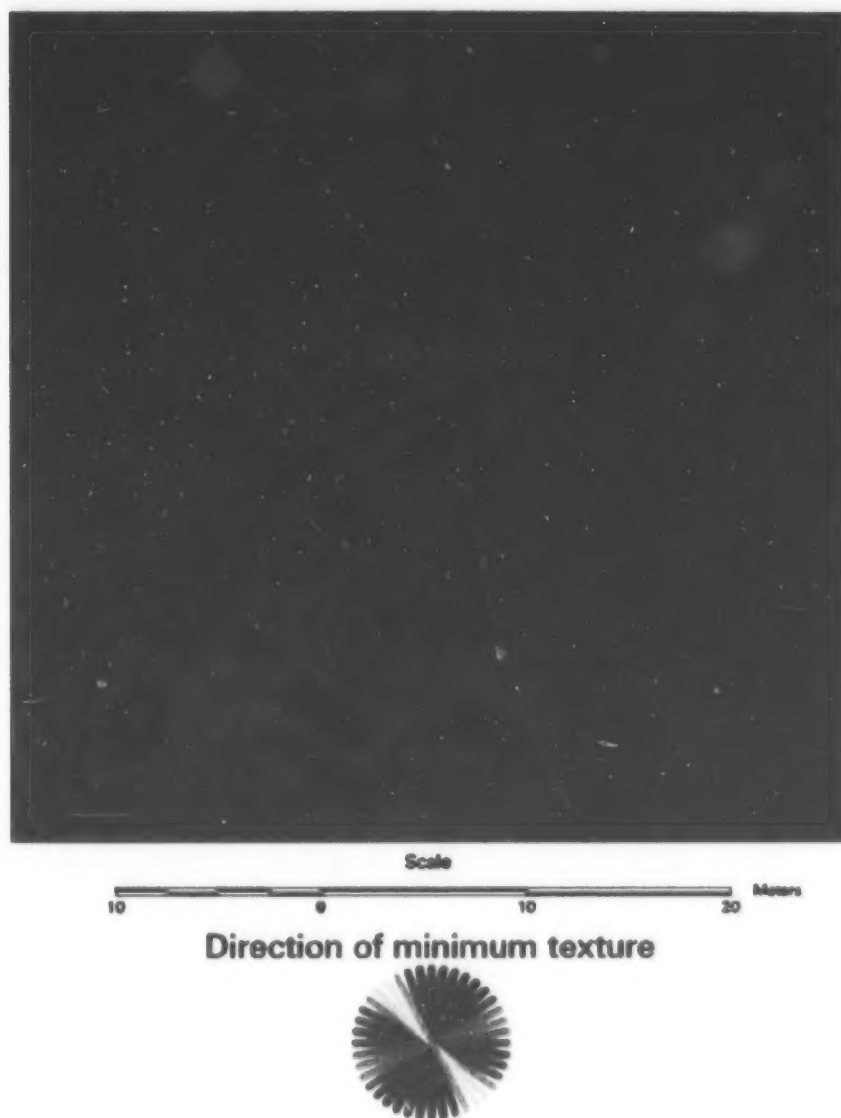


Figure 6. Direction of (11 by 11) minimum texture in shadows. White lines are borders of trees identified through photo-interpretation.



COMPARISON OF TWO TREE APEX DELINEATION TECHNIQUES

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ABSTRACT

High-pass filter and double aspect techniques were utilized to identify aspen tree apexes upon black and white archival aerial photography. In order to individually assess techniques, synthetic images were created incorporating differing image and stand characteristics. Synthetic variables included differing density, crown size, and image noise variations. The algorithms isolated apexes through detection of local gray-scale maxima corresponding to the illuminated tree tops. Intermediate results showed techniques were acceptable for dense regularly spaced tree stands of similar height and uniform illumination. At higher image resolutions, crowns commonly displayed multiple apexes which necessitated the amalgamation of peaks. A cumulative pixel traversal (cost surface) function was adopted as a technique for delineating illuminated crown perimeters and for merging apexes upon single crowns. These algorithms were used for temporal modeling of forest structural changes associated with an acid mine site.

Keywords: tree delineation, trembling aspen, acid mine drainage, environmental degradation, high-pass filters, segmentation, archival aerial photography.

RÉSUMÉ

COMPARAISON DE DEUX TECHNIQUES DE DÉLIMITATION DE FLÈCHES D'ARBRES

Des techniques du type filtre passe-haut et bi-aspect ont été utilisées pour déterminer les flèches des peupliers faux-tremble à partir de photographies aériennes d'archives en noir et blanc. Afin d'évaluer chacune des techniques, on a créé des images synthétiques comportant des caractéristiques différentes d'image et de peuplement. Les variables synthétiques comprenaient des densités, des dimensions de houppiers et des variations bruit image diverses. Les algorithmes ont permis d'isoler les flèches par le biais de la détection de maximums locaux dans l'échelle de gris qui correspondaient aux cimes éclairées. Les résultats partiels ont indiqué que les techniques utilisées étaient acceptables dans les peuplements denses de hauteur similaire avec un éclairage uniforme, où les arbres sont régulièrement espacés. À des résolutions d'image plus élevées, les houppiers présentaient des flèches multiples qui nécessitaient la fusion des crêtes. On a adopté une fonction cumulative de traversée de pixel (superficie exploitable) comme technique permettant de délimiter les périmètres des houppiers éclairés et pour joindre les flèches en houppier unique. Ces algorithmes ont été utilisés pour réaliser la modélisation temporelle des changements forestiers structuraux associés à un site d'eau d'exhaure acide.

INTRODUCTION

This paper is a portion of an ongoing study to observe long term environmental degradation and forest structural changes on a site affected by acid mine drainage (King, 1997,1996,1995; Levesque and King, 1995;

Seed and King, 1997, Walsworth and King, 1997, Walsworth, 1998). The objective was to undertake a preliminary integration of temporal imagery utilizing standard GIS tools, and assess difficulties of identifying canopy changes utilizing uncalibrated black and white imagery. Symptoms of damage are expressed in tree morphological changes, stunted growth, less foliage, early senescence and death. The implementation of a tree delineation methodology can therefore provide an estimate of vegetation decline and offer a means for indirectly assessing contaminant diffusion. The methodology of extracting objects or classes of objects from imagery is called segmentation. This paper reviews some general segmentation categories, followed by an illustration of a gradient guided implementation utilizing local maxima as seeds for the tree delineation.

BACKGROUND

Haralick and Shapiro (1985) outlined several segmentation techniques in a summary article which, although not directly applied to tree delineation, showed how methods are frequently a hybridization of techniques utilizing tonal and spatial components within the imagery. Routines employing edge and gradient measures are of particular interest for forest applications and are highlighted in this summary as an introduction to the tree delineation method. Adopting Haralick and Shapiro's terminology, three segmentation categories appear appropriate to the problem of tree delineation on single band imagery:

- 1) Measurement-space guided spatial clustering
- 2) Region growing
- 3) Spatial clustering.

MEASUREMENT SPACE-GUIDED SPATIAL CLUSTERING

The simplest technique in this category is probably gray-level clustering. The technique is based upon recognition of peaks within the gray-level histogram. The difficulty with the technique is that the spatial relationships of the gray-tone values are not considered, added to which, the histogram modes are frequently not well developed, the net result being that segmentation can often suffer from noise. An enhancement is to utilize small area masks to highlight and merge local histogram clusters (Chow and Kaneko, 1972) or to simplify the image through smoothing (Nagao and Matsuyama, 1979). An alternative to purifying areas is utilization of edges enhanced with the use of High-pass filter operations. The theoretical basis for these approaches is that a histogram, generated from the high contrast mask, will have equal numbers of pixels from the foreground and background, and hence, should enhance histogram cluster separability (Weszka et al. 1978). An intermediate solution was undertaken by Panda and Rosenfeld (1978) who transformed an image into two-dimensional space consisting of gray tone intensity and gradient magnitude. High gradients were considered likely at an edge between regions and which through projection could form a decision boundary separating foreground and background low gradient elements.

REGION GROWING

Pure region growing algorithms, in contrast are spatially explicit forming linkages between adjacent pixels and/or regions that have "similar" properties (Bryant, 1979; Asano and Yokaya, 1981). "Similarity" usually takes the form of a threshold cutoff based upon the absolute difference between gray-tone intensities, or for area comparisons, either a t-test or the difference normalized with the paired differences for the entire area. Edge detection techniques have also been utilized within region growing algorithms (Pong et al. (1984), Jarvis and Patwick, 1973). Roberts and Sobel operations have been used to remove segmentation gaps (Haralick and Dinstein, 1975) and used to create segment enclosures which can be filled to form regions (Perkins, 1980; Pavlidis and Liow, 1990). Haralick (1980) suggested fitting a plane to the neighbourhood, or on either side of a pixel, and testing to determine if the slope was zero or if the coefficients of fit were similar; if this was not the situation an edge was assumed. Woodcock et al. (1983) used this slope-facet model to segment rugged forest landscapes.

SPATIAL CLUSTERING

Spatial clustering is an attempt to combine segmentation in measurement space with region or spatial linkage techniques. Haralick and Kelly (1969) used histogram peaks as seeds, combining both spatial and measurement region growing clustering away from these peaks. An alternative algorithm is to iteratively apply differing measurement intervals so that a generated segment maximizes its coincidence with a border defined by an edge operator (Milgram, 1979). Instead of only utilizing edge geometry, gradient-guided segmentation can enhance segmentation directing it towards an edge (Minor and Sklansky, 1981). Spatial clustering may also be applied within an aggregated pyramid structure, which as found within many split and merge methodologies consecutively divide an image until each portion is tested as being homogeneous using measures such as sample variance and range.

Although a very condensed summary, there is a rich body of work utilizing filters to enhance segmentation.

TREE IMAGE CHARACTERISTICS AND TREE DELINEATION

Currently at the metre image pixel scale-range the most popular method for identifying tree apexes are local-maxima derived from kernel based high-pass filter methodologies. The difficulty is that they may be dependent upon image resolution and kernel dimensions. Ideally, if tree apexes are to be identified kernel dimensions should match tree dimensions, but this is problematic for natural forests which portray a wide crown size range and hence require additional information to adapt the filter window. Another problem at higher resolutions and particularly at sites exhibiting damaged deciduous crowns are the occurrence of multiple tonal maxima corresponding to the internal branching structure (Levesque, 1995). An alternative developed by Gougeon (1995) was to utilize interstitial shadows to delineate crown perimeters. This is effective on crowns with well defined interstitial shadows. Past a certain tree density, however, edges commonly become inter-branched causing clumps which reduce the population estimate. In such circumstances corroboration with gray-tone image maxima delineating tree apexes is a potential methodology for overcoming difficulties. This paired apex shadow approach has been employed to purify counts within sparse stands in which numerous false peaks are associated with the background (Gougeon, 1997) and suggests that utilizing peak-shadow pairs may be a fundamental criteria for tree recognition.

METHOD

This research has adopted similar tree delineation approaches discussed above, but favors delineation as a peak-shadow pairing process utilizing a double aspect technique. The methodology is organized in two sections:

- i.) preliminary comparison between two apex finding techniques utilizing a synthetic data set.
- ii.) the application of apex techniques to archival imagery and expanding the method showing how a pixel traversal surface sometimes called a "cost surface" can be used to segment crown boundaries.

COMPARISON DOUBLE ASPECT AND HIGH-PASS FILTER LOCAL MAXIMA FINDING TECHNIQUES

Two primary techniques were implemented and compared; a high-pass filter and a double-aspect technique. Both take advantage of brighter tones coinciding with the center of the tree crown. The high-pass filter technique enhances high frequency data within an image. For practical purposes it may be visualized as the difference between the image and it's smoothed equivalent enhancing apexes and lows. The difficulty is that it is a measure of contrast so that for flat crowns only edges may be enhanced. The double aspect technique has been employed by Iisaka (1998) for metallurgical analysis of steel and is similar to Haralick's slope facet model but is based upon slope direction only or sign of the first derivative. It employs a double calculation of surface aspects, undertaken for each of four directions (N-S, E-W, SW-NE, SE-NE) forming ridge and gully lines (Figures 1,4). When the lines are overlaid, the intersection of ridges represent apexes, while the union of gully lines represent edges.

Tree apexes interpreted from the two recognition methods were tested both against a synthetic data-set in which differing noise levels were applied and against manually interpreted sub-windows. Each test was assessed for its tree-count estimate, errors of omission and errors of commission. Manual delineation comparisons additionally assessed the threshold brightness at which apexes became visually recognizable.

The synthetic dataset represented trees as cones developed by a smooth dilation away from a set of random points of varying density. The conical values were then stretched to occupy a range between 50 and 200 approximating the gray-levels found within the photographic imagery. To make the model more realistic, noise, shadow and texture were added. Noise was added using normalized random variance applied at differing amplitudes. Shadows were calculated using the Idrisi GIS hill shading module, which by applying an azimuth angle and a zenith angle, calculated the illumination via the cosine of the incidence angle (Bonham-Carter, 1994). Lastly, crown texture was modeled by replacing the smooth dilation away from the points with an uneven but constantly decreasing dilation formed using a "cost" surface over a random image and then shadowing. Trees in all cases were interpreted with a fixed radius of 8 or 5 pixels radius for large and small tree classes respectively, excepting densely packed areas in which pixels were assigned to the closest apex. Results were compiled as the percentage of polygons correctly identified. To assess the identification of false peaks, which are composed of multiples and misses, a second tally was employed which subtracted the number of peaks correctly identified from the total number of calculated apexes and normalized this with the correct number to produce an omission or commission error.

Manual count comparison consisted of a 100 by 100 pixel window taken from the scanned photographs. Trees were then interpreted manually from the contrast enhanced images and compared to double-aspect and high-pass apex recognition. Crown comparisons were based upon a 10 class linear brightness scale of the area around the apex. Unfortunately the correctness of the derived apexes from the air photography could not be assessed by ground measures due to the difficulty of accounting for temporal changes.

DELINEATION OF CROWN EDGE

Preliminary testing showed that union of all gully lines provided only a partial delineation of edges. To fill in the edge boundaries it was decided to allocate the areas surrounding the peaks as a function of proximity and brightness, utilizing the partial edge boundaries as fences to the allocation process. This process consisted of inverting the gray tone images so that light areas had low values and dark high, ranging between 0 and 255. The inverted surface can be likened to a cratered surface, in which the former apexes occupy local minima and the walls of the craters form irregular boundaries of variable elevation. Employing a flooding model methodology implemented as a pixel growing algorithm, in which apexes are seeds, pixels surrounding the crown polygon are aggregated by order of brightness. Allocated areas soon contact along the lowest portions of the crater walls and then fill to higher areas forming a surface, which, if the cumulative traversal sums are maintained along the diffusion path, is referred to as a "cost surface" (Figure 1). The "cost function" works by assigning every pixel the minimum cumulative cell traversal sum away from a set of points. In this example the set of point seeds are the tree apex centroids. The Idrisi "cost" function was employed to approximate this, forming gray-tone weighted proximity surface or *isodapane* surrounding the centroid which could be allocated to a parent seed apex creating a Theissen-like division of space. Removing the gully fence pixels and normalizing the cost surfaces in relation to the maximum value for each polygon produced a proximity surface pixel rank between the central peak and the shadow edge, in effect forming a bowl of ranked thresholds between 0% to 100% allowing a means of flexibly defining an edge. This methodology is demonstrated upon a tree image and some preliminary modifications discussed.

PRELIMINARY RESULTS

SYNTHETIC IMAGE TESTS

Noise Effects

The synthetic image formulation resulted in an image with flat and broad peaks, which had ill-defined edges in densely packed areas. Figure 3 shows some examples of these test images and apex results. Synthetic

image profiles have been graphed in Figure 2. The high-pass filter methodology proved to be the most effective over the variance range (Table 1) although the double aspect methodology attained its best results with random noise values similar to that found within the photography (variance = 30). Trends show that the double-aspect results improved greatly when some variance was added to the imagery whereas the high-pass method proved susceptible to added variance. The relative improvement of the double aspect method was primarily due to the replacement of flat-domed apexes characterized by sharp but non-intersecting aspect contacts with diffuse directional-aspect contacts which have higher potential for intersection. In all situations, addition of noise or high frequency had the effect of broadening derived peaks as evidence by the larger delineated points. At lower noise values omission errors dominated and may be a result of poorly defined divisions between trees within high density clumps. Both techniques showed degradation of their recognition abilities from image flatness and noise. The combination of flat crowns and noise, however, does not appear to compound any errors.

		Smooth	Var = 5	Var = 15	Var = 30	Shadow	Texture
Double Aspect	Percentage Identified	68%	50%	54%	95%	88%	92%
	Multiples/Misses	-7%	-20%	-13%	-11%	+29%	+78%
High -Pass	Percentage Identified	84%	96%	83%	88%	90%	92%
	Multiples/Misses	+2%	-12%	-1%	+21%	+34%	+104%

Table 1. Apex delineation accuracy with noise, shadow and texture (+ commissions, - omissions).

Shadow and Texture Effects

The remaining tests qualified shadow and texture effects upon apex counts. Profiles illustrated in Figure 2 show displacement of the maximum illumination center toward surfaces incident to the illumination ray, in this example to the west (left). A secondary effect of shading was an overall increase in contrast with profiles showing a replacement of conical shapes with boxed profiles and poor apical development. Interpreted tree centers were similarly displaced toward the illumination source, in many situations becoming compromised due to displacement out of the immediate polygon. The uneven dilation proved to create a fairly mottled image ("Rough" in Figure 3). Textured surfaces showed that many small false peaks were added as the result of the low angle illumination, highlighting difficulties associated with deriving tree counts utilizing solely a maxima methodology without any prior knowledge of surface geometry.

COMPARISON TO MANUAL DELINEATION

Comparison between automated and manual counts show good agreement although the double aspect did find small manually unrecognized peaks in the shadows, in the lower quarter of the gray-scale histogram. These shadow peaks were subsequently removed for crown delineation (Figure 4,5). High pass filter counts utilizing a 3 by 3 window highlighted edges upon larger crowns but provided better correlation with intermediate crowns which had good separation. Tree counts showed that the double-aspect method produced higher counts than the high-pass filter method with additional peaks occurring predominantly in the shadows. The most striking observation along the temporal data sequence was found to be a significant increase of derived stem counts from 1949 to 1990 despite similar spatial scales and comparable dynamic ranges (Figure 6). This can be attributed to better illumination, particularly within the 1979 image, less blur, greater contrast due to better film fidelity and improved resolution of the later photography. In the 1979 and 1990 images middle to understory trees became recognizable. Unfortunately, noise also increased with sensitivity and resolution, thus false identification of peaks also became more numerous in more recent imagery. This created a dilemma for understanding of temporal changes in individual tree stems and which eventually led to interpreting changes based upon local density averages and the assumption that distal areas were temporally unaffected by tailings degradation. Preliminary temporal comparisons between images showed that average tone was highly variable between images, but a threshold average contrast derived from a high-pass filter did portray the forest tree classes fairly well.

DISCUSSION

Within single deciduous crowns the occurrence of multiple apexes is an expected consequence of higher resolution. Two enhancements are proposed as a means of aggregation. The first is an amalgamation method following the rationale that if multiple points occupied a single crown there would be a relatively small distance between them and they would share a side. Therefore again, using a bowl analogy, if each bowl is filled, the liquids would merge at relatively lower fill volumes than those areas segregated by deeper shadows (Figure 1), so by defining a threshold value in the lower range (10-30%), filled crowns which contact along an edge may be merged. Presently, the methodology undertakes limited merging of crowns based upon a single threshold for the entire image. Ultimately, local image characteristics like local contrast must be considered. Implementation of a gray-scale traversal weighting is probably best applied on a semi-automated cursor driven process in which an operator identifies areas requiring attention and the computer undertakes the merging and keeps track of the weighting surfaces.

The second methodology which has been preliminarily examined consists of running the apex finding routines upon multiple filtered input images. Filtering has the effect of generalizing, shifting and flattening small gray-tone perturbations, so that the combination of apexes from successively filtered (mean of a 3 by 3 moving window) images would make a dense cloud of stem points which could then be replaced with a single centroid. This methodology has the added benefit of allowing flat topped peaks often found in overexposed images to be assigned apex centroids, since flat topped peaks show a depression of perimeter DN values coincident with smoothing. Plotting apex counts as a function of smoothing showed that peak numbers decreased and fewer differences were evident with each iteration as the smaller peaks followed by larger peaks were smoothed with the accompanying loss of definition (Figure 6). The rate of change was highest for the latest images. Unfortunately, the curves cannot simply be extrapolated to form a correction factor since rates are not linear nor similar and is indicative that differing combinations of causes were involved, the obvious ones being image geometry, view angle and shadow. Consequently, any corrective inter-temporal normalizing methodology will be image specific and for this example complicated by the fact that the area is subject to canopy degradation the consequence of which is the creation of canopy openness allowing understorey and ground features to be visible from the air. This led to an interesting consideration of degradation, in that depending upon scale, one should actually expect increased stem counts and texture within degraded forest, in which the unifying spatial properties of larger trees are diminished due to damage or death. Due to the added tree size heterogeneity increased illumination problems can result.

Therefore, confining observations to temporal changes of larger crowns has advantages in that they are less likely to be in shadow and hence may show more continuity (Walsworth and King, 1997). This tree sampling methodology utilized the conical shape through integrating the high-pass filter values over individual crowns as an indication of a canopy class and in turn gridding these accumulated values. These values could then be classed to visually match the dominant FRI interpretation for the area with the local differences a possible indication of canopy change (Walsworth and King, 1998). The tree apex and window sampling combination however is not a replacement for individual tree comparison, but appears to occupy a procedural position intermediate between aggregate texture techniques found within Gray-level co-occurrence matrices (Haralick 1973) and the natural pre-attentive approach utilizing first order statistics via a Triangular Primitive Network proposed by Hay et al. (1994).

The double aspect technique of decomposing imagery into directional components can provide a preliminary appreciation of tree size, density, and illumination characteristics. For example, in homogeneous areas, changes in the harmonic nature of the aspects across the image could be indicative of changes associated with forelit and backlit illumination conditions and may potentially provide a means for automated correction. However, the fact that the double-aspect method did not show good interpretation upon smooth images is disappointing and can probably be compensated for by developing a wider ridge definition range. This would require an additional slope calculations which may not be practical considering that high-pass filters may also be applied with directional weightings and adaptive windowing. It appears the high-pass filter methodology is the preferred for determining maxima but may be enhanced with the incorporation of an aspect calculation for determination of optimum window size.

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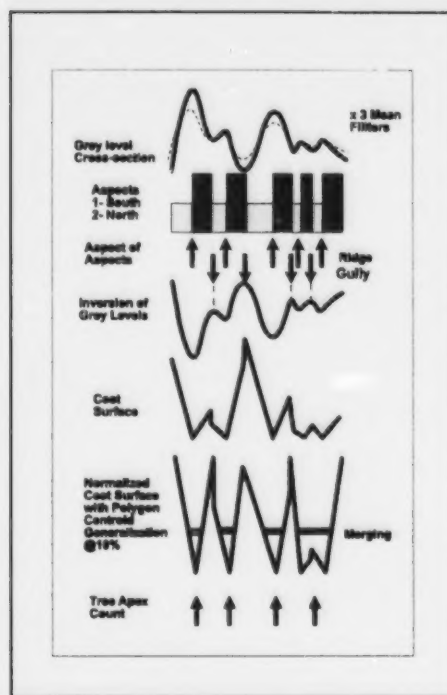


Figure 1. Double aspect and subsequent merging methodology.

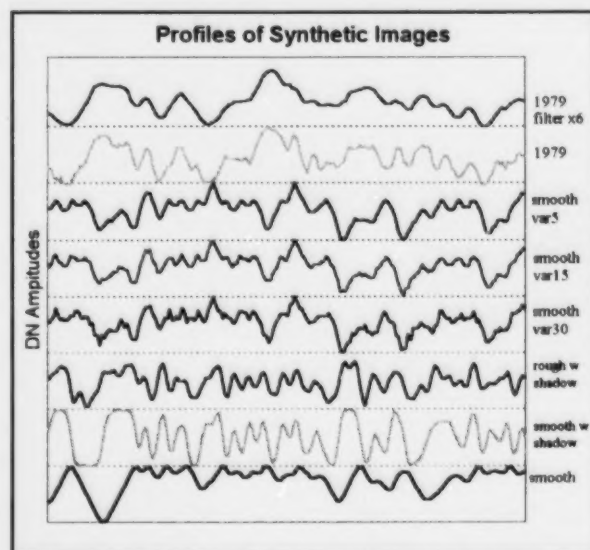


Figure 2. Gray-level profiles (200 pixel width).

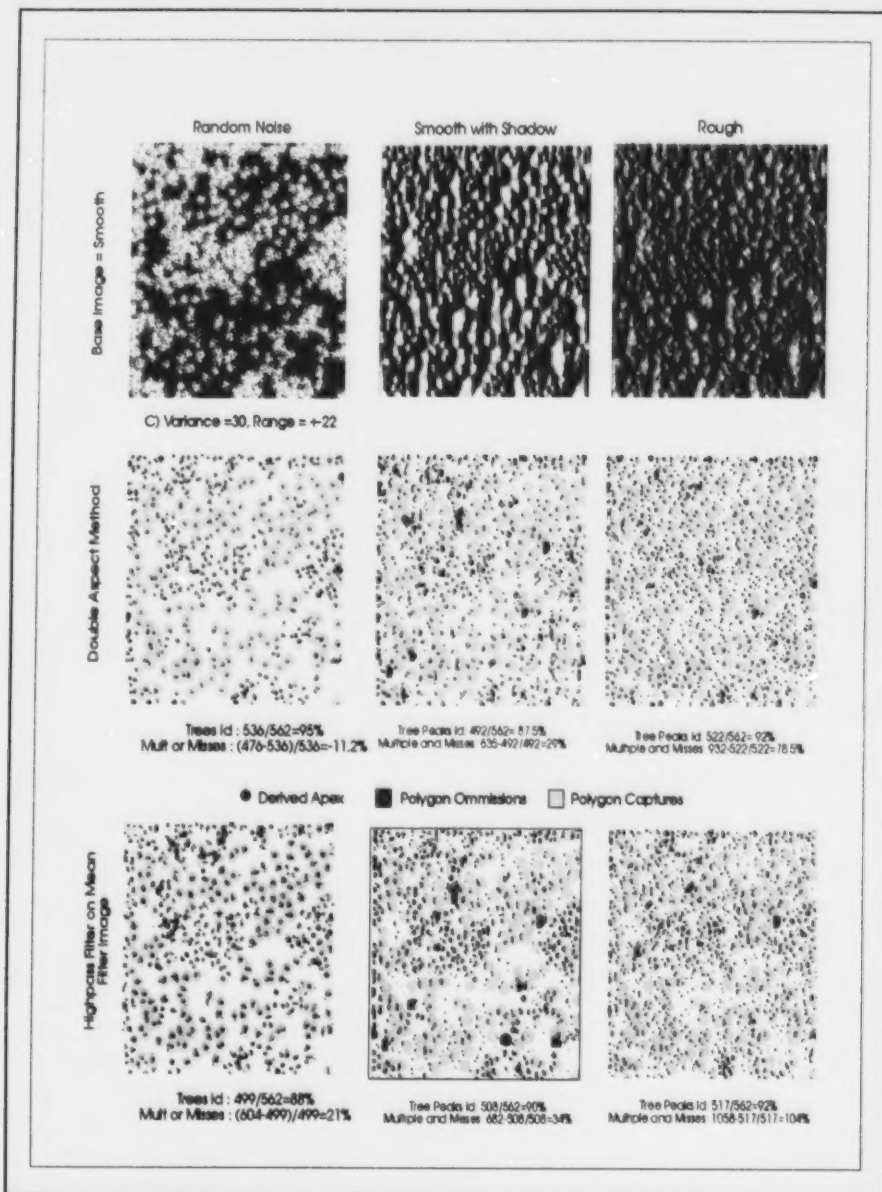


Figure 3. Examples of high-pass, double-aspect apex derivation with noise, shadow and texture.

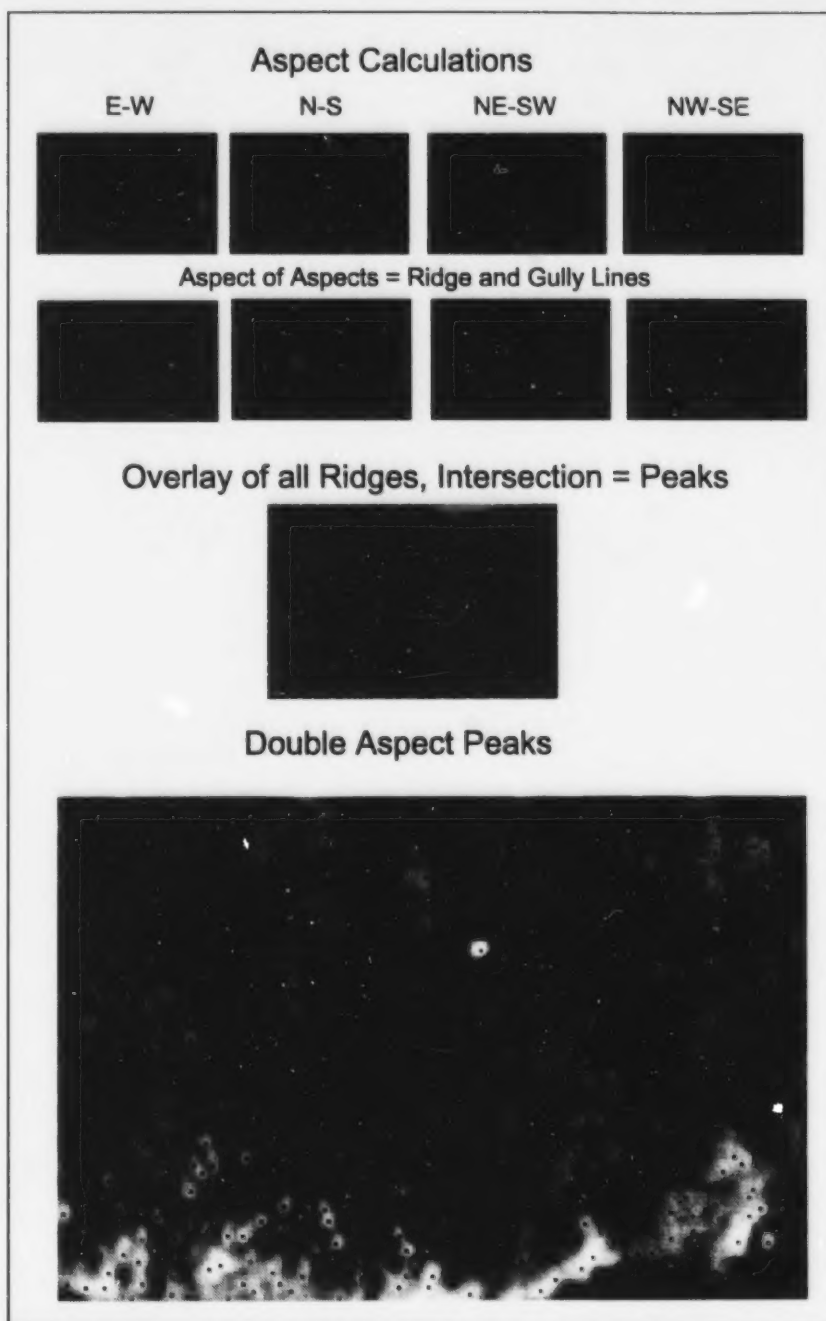


Figure 4. Application of the double aspect method to gray-tone imagery.

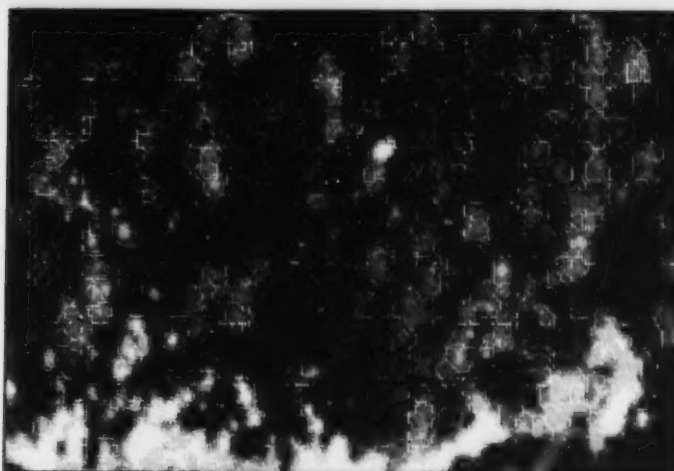


Figure 5. Preliminary tree crown delineation derived by setting the cost surface threshold at 40% but requiring some individual tree customization criteria for setting threshold criteria (upper left corner of Figure 4).

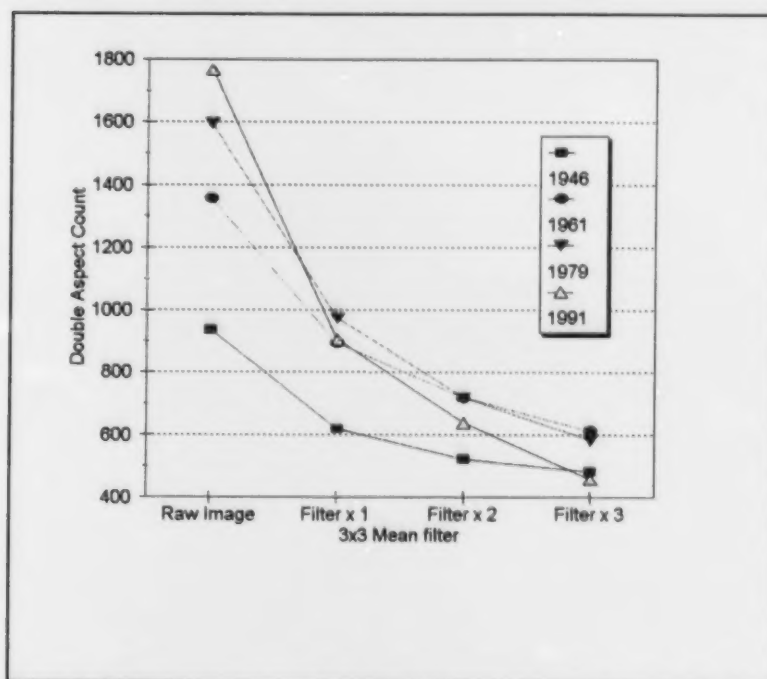


Figure 6. High-pass apex counts for differing image dates as a function of smoothing showing differing rates of decline.

AUTOMATED TREE CROWN IDENTIFICATION USING DIGITAL ORTHOPHOTO MOSAICS

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ABSTRACT

Forest inventory collates mensurational data interpreted directly from remotely sensed imagery, or derived indirectly from information interpreted from the imagery. Currently, the predominant scale mapped is at the stand level, however, due to the increasing availability of high resolution (or hyperspatial) digital data the possibility of applying high automated techniques to deriving these attributes is increasing.

A number of studies have been carried out to utilize hyperspatial multispectral data for forest mensuration. These have focused on the automated delineation of individual tree crowns. Digital orthophotos however have not been as yet extensively used for this purpose. This paper reports on the initial results of a procedure developed to identify and map tree crowns from digital orthophoto mosaics.

RÉSUMÉ

IDENTIFICATION AUTOMATIQUE DES HOUPPIERS À L'AIDE DE MOSAÏQUES ORTHOPHOTOGRAPHIQUES NUMÉRIQUES

L'établissement de l'inventaire forestier permet de recueillir des données de mesure qui sont interprétées directement à partir de l'imagerie télédéetectée ou dérivées indirectement à partir de l'information interprétée d'après l'imagerie. Présentement, l'échelle prédominante cartographiée se situe au niveau du peuplement, mais, en raison de la plus grande disponibilité des données numériques (ou hyperspatiales) à haute résolution, on a de plus en plus la possibilité d'appliquer des techniques hautement automatisées pour calculer ces attributs.

L'utilisation des données multispectrales hyperspatiales en dendrométrie a fait l'objet d'un certain nombre d'études qui ont porté essentiellement sur la délimitation automatique des houppiers. Cependant, les orthophotographies numériques n'ont pas fait l'objet d'une utilisation aussi poussée à cette fin particulière. Ce mémoire présente les résultats initiaux d'une procédure mise au point pour délimiter et cartographier les houppiers à partir de mosaïques orthophotographiques numériques.

INTRODUCTION

Forest inventory collates mensurational data directly from remotely sensed data or derived from information interpreted from imagery. Standardized procedures exist for the extraction of forest attributes from

conventional aerial photographs using manual photointerpretive techniques (Resource Inventory Committee, 1996). Many of the forest attributes (Table 1) identified can, however, be extracted consistently through the use of more unconventional imagery such as airborne multispectral data and digital orthoimagery. The promise of new, high spatial resolution (hyperspatial) and high spectral (hyperspectral) data will lead to an increased emphasis on the use of digital techniques to extract the required forest attributes.

Much of the work to date relating remote sensing techniques to forest inventory has involved the use of spectral measures derived from satellite data to extract vegetation characteristics. A few studies have attempted to use the spatial characteristics of satellite data to attempt to characterize forest environments (Cohen et al. 1990). There has been an increasing recognition, however, that these textural measures are most useful when the pixel size approaches the size of the forest object (that is the tree) that is being described (Woodcock and Strahler 1987, Marceau et al. 1994, Hay et al. 1997). This has led to an increasing use of hyperspatial multispectral scanner data to extract both spectral as well as spatial attributes (Gougeon 1997, Pollock 1996).

This latter approach, of using hyperspatial data to extract the structural elements of the forest scene, appears to be extremely promising, having achieved a high degree of success identifying both the extent of the individual tree crown as well as the specie (Gougeon 1997). The methods adopted by the approach developed by others relies on submetre spatial resolution multispectral data, however, which are both expensive to acquire and process. An alternate approach was developed to circumvent this reliance on high resolution multispectral data and is based on the use of panchromatic orthoimagery. This type of imagery is relatively inexpensive and accessible. The major disadvantage is that it is commonly panchromatic and so does not allow for the optimization of the image based on spectral enhancements. The method focuses on the identification and mapping of the location of tree crowns rather than the delineation of the entire crown.

METHODS

The main assumption adopted for the detection of individual trees is that the reflectance off a tree crown, in this case the work is restricted to conifers, is greatest at its apex, also assuming that the imagery is collected when the solar elevation is highest. The reflectance then decreased towards the sides of the crown. This point is illustrated in Figure 1 where a 50 by 50 metre window from an orthophoto (1 metre resolution) is plotted. The Z values in this case is not the height of the tree but rather the grey tone extracted from the orthophoto. It is clear from this that the individual trees can be identified from the plot.

To map the individual crowns a relatively simple search mechanism was developed to locate the highest reflectance value within a roving matrix (see Figure 1). The search algorithm checks the central pixel value with respect to the enclosing pixel values. Once one such value has been located then its location is recorded. The individual points can then be exported as X-Y coordinates and imported into other applications.

In many instances it has been found that the logic designed to detect the individual tree crowns occurs as a random distribution over ground cover that is not composed of tree crowns (Figure 2). These sites would normally be identified as being tree tops. They can, for the most part, however, be eliminated due to the range in values surrounding the local maximum. In the case of tree crowns the range of values within the 3 by 3 window has been found to be considerably greater than that found in areas where the patterns occur due to a random distribution. A user specified range of values has therefore been implemented which allows for the filtering of those sites where the range is less than that specified.

RESULTS AND DISCUSSION

To test the tree crown finding a digital orthophotomosaic was constructed using 1:30 000 scale panchromatic aerial photographs. The photos were scanned to a resolution of 1 metre, orthorectified, and mosaicked. Areas were selected from the orthomosaic which contained examples of a range of crown closures and patterns (Figure 3). The crown-finding algorithm was applied to these various sites.

To assess the accuracy of the approach a subsample of the image window, corresponding to approximately 15% of the entire area, was randomly selected. The locations of the individual tree crowns were manually interpreted within this window and transferred to the orthoimage. A comparison of the two interpretations yielded a correspondence of 70% to 85%, depending on the crown density and the tree size.

The level of correspondence between visually interpreted tree tops and those obtained from this method is dependent on a number of factors. The first is the level of detail contained within the digital imagery. The level of detail contained within orthoimagery gridded to a common pixel resolution is dependent on the scale of the original input imagery (Bergmans, 1997). A cause for misinterpretation is related to the relationship between the crown size and the pixel size. This problem is analogous to the relationship outlined by Woodcock and Strahler (1987). The most common situation is one of the pixel size being too coarse in relation to the crown. Similarly, at the other end of the size spectrum, where the pixel size is much smaller than the object, there may exist a more than one contiguous peak pixel defining the crown. In this case also the logic used in this work will not be satisfied and the crown not mapped. Figure 4 shows the difference in detail between the 1 metre orthoimagery collected from 1:15,000, 1:40,000 and 1:70,000 scales. It is evident that the detail collected from these images differs and so, therefore, will the possibility to detect the individual crowns.

While the output crown images are in themselves of potential interest to extract the reflectance characteristics for individual crowns, especially if one is using hyperspatial, a more realistic use for inventory purposes is the grouping of the crowns detected into an image denoting the density in crowns per unit area (commonly per hectare) (Figure 5). This image can then be used directly in an inventory application or vectorized and imported into a CIS together with data from other sources.

CONCLUSIONS

This study has demonstrated a simple method to extract the location of tree crowns from digital orthophotomosaics. The method, while relatively simple, does yield a comparatively accurate estimation of the location of stems. Given the simplistic model used to detect the crowns, the resolution of the data necessary is coarse in comparison to other more complex methods. The advantage of this method is that it can readily be integrated into forest inventory methodologies in terms of mapping out the density of stems per unit area.

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- tree cover pattern
- tree crown closure
- tree layer
- vertical complexity
- species composition
- age (leading and second species)
- age confidence index (leading species)
- height (leading and second species)
- height confidence index (leading species)
- basal area
- basal area confidence index
- density
- snag frequency

Table 1. List of forest stand attributes identifiable from aerial photographs. (Source: Resource Inventory Committee, 1996)

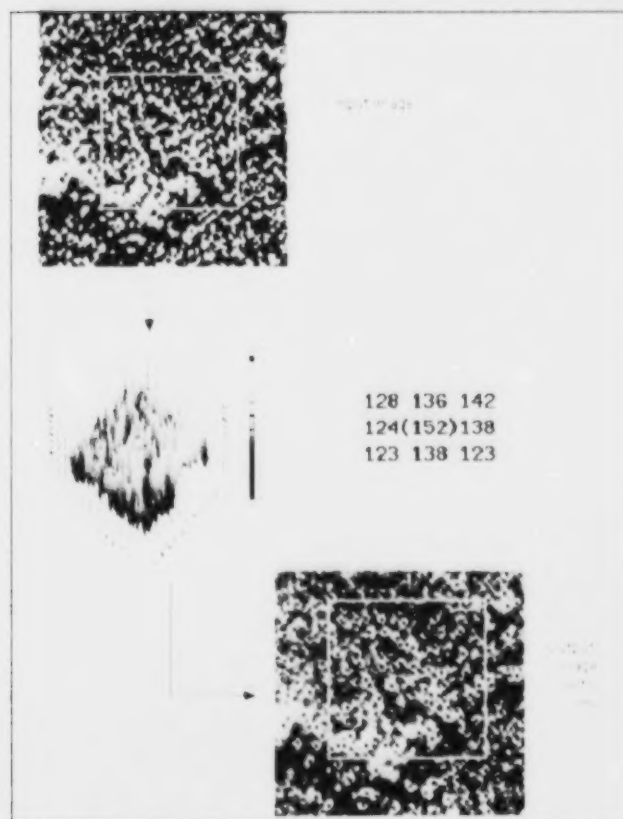


Figure 1. Tree finding strategy

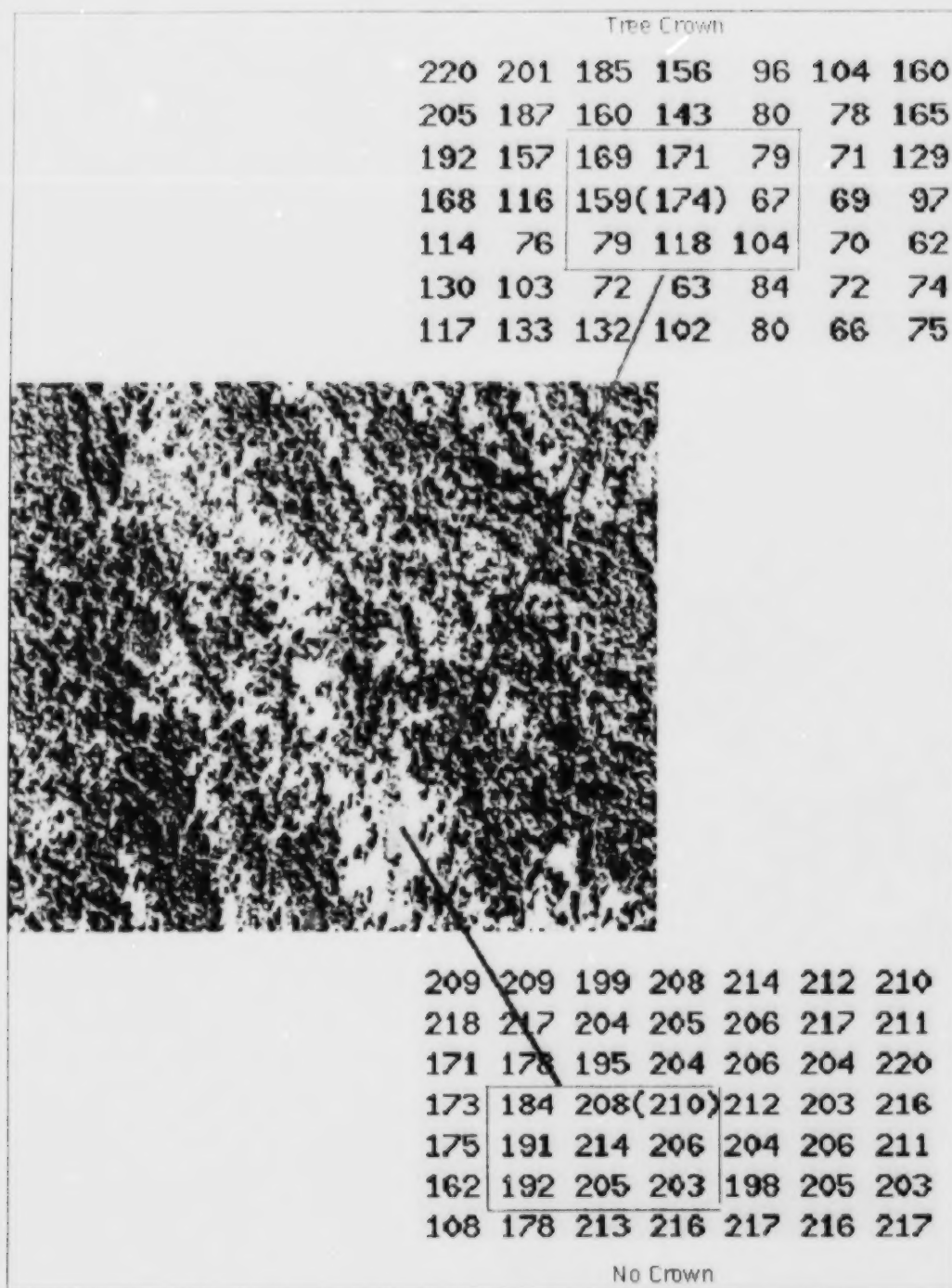
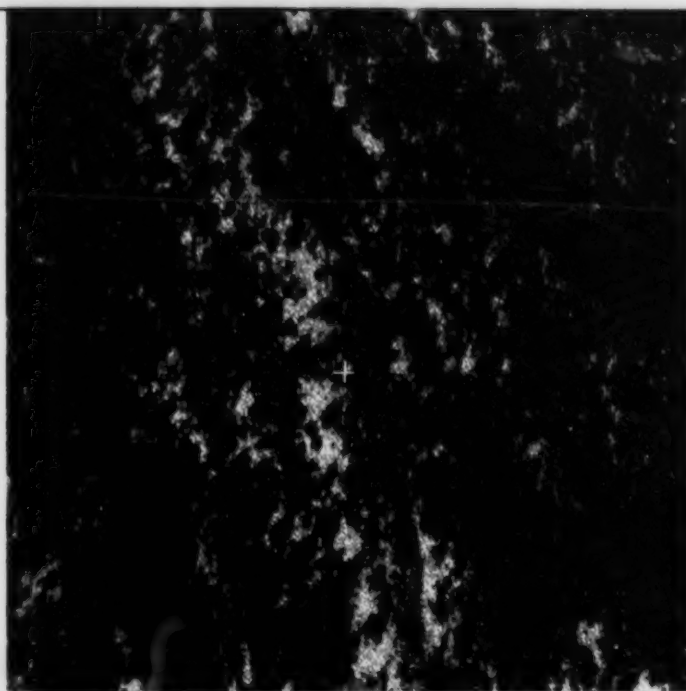


Figure 2. Comparison of treed and non-treed areas which satisfy the tree finding logic.

Image Input



Crowns Output

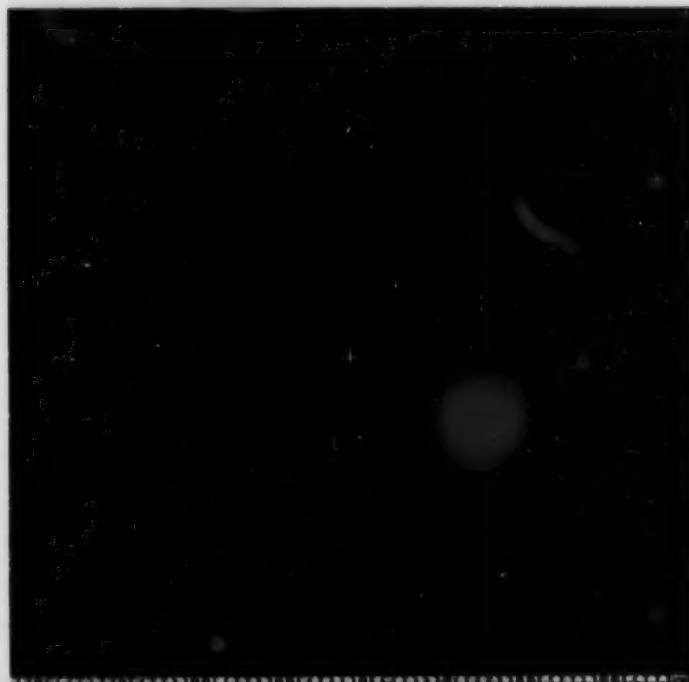


Figure 3. Results of tree finding procedure applied to 1 metre orthophoto.

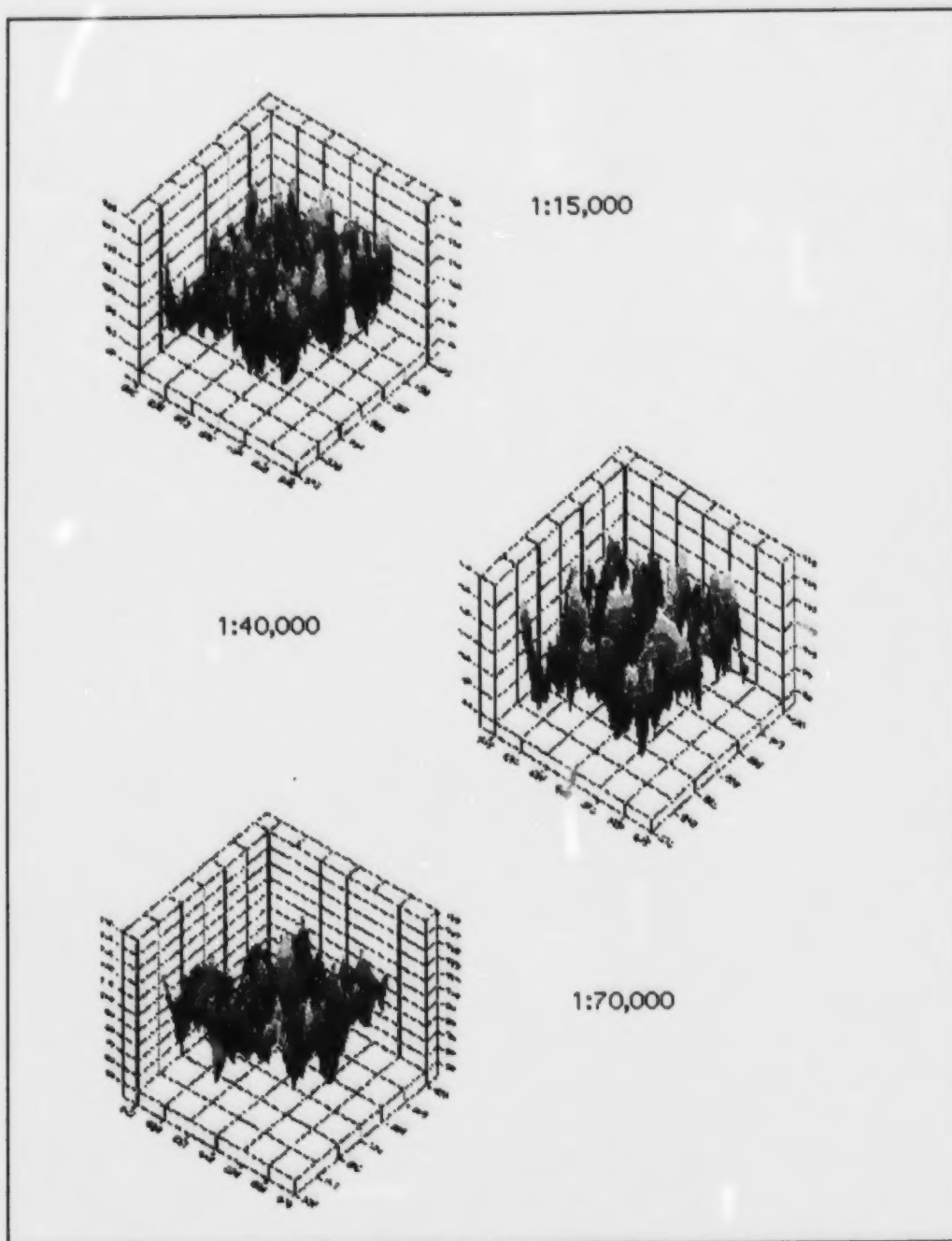
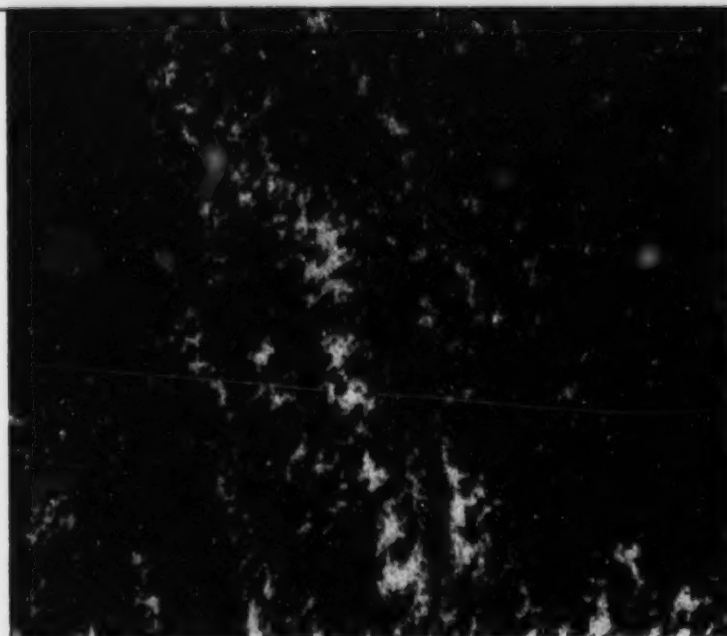


Figure 4. Comparison of 1metre orthophoto derived from aerial photographs with different scales.

Original
Image



Crowns / Unit area

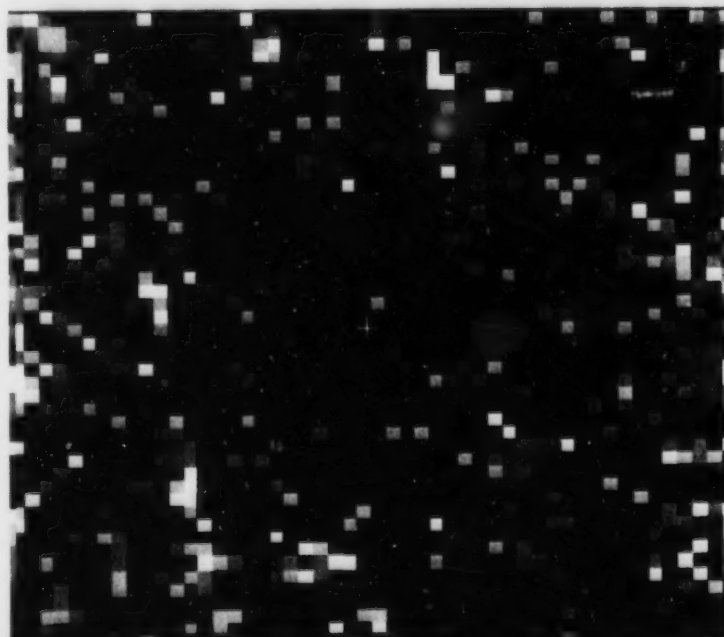


Figure 5. Results of summary of procedure showing crowns per unit area.



VORONOI DIAGRAMS, EXTENDED AREA STEALING INTERPOLATION AND TREE CROWN RECOGNITION: A FUZZY APPROACH

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ABSTRACT

In this paper we describe an application of Gold's and Lowell's work to the case of individual tree crown characterization in a deciduous/mixed cover. It represents the first state of a research agenda that ultimately aims to define a highly adaptive interpolation approach in order to improve the management of differential uncertainty of multi-source data and the fuzzyness of spatial variability that characterizes the natural structure of deciduous/mixed cover types. Our primary objectives are to evaluate the utility of the theft interpolation method in combination with fuzzy logic rules to quantify and characterize the spatial extent of individual crowns and to illustrate the potential of extensions to the theft method that accommodates the presence of holes in the canopy, notably gaps and interstices.

RÉSUMÉ

DIAGRAMMES DE VORONOI, INTERPOLATION PAR SUBSTITUTION D'AIRE ÉTENDUE ET RECONNAISSANCE DES HOUPPIERS : APPROCHE FLOUE

Le présent mémoire porte sur la description d'une application des travaux de Gold et Lowell portant sur la caractérisation des houppiers dans une forêt décidue/mixte. Il s'agit de la première étape d'un plan de recherche qui vise en bout de ligne à définir une approche d'interpolation adaptative dans le but d'améliorer la gestion des incertitudes différentielles provenant des données multisources et le flou de la variabilité spatiale qui caractérise la structure naturelle des types de couverts décidus/mixtes. Nos principaux objectifs consistent à évaluer l'utilité de la méthode d'interpolation de substitution combinée à des règles logiques floues pour quantifier et caractériser la portée spatiale des houppiers; et pour illustrer la capacité potentielle d'extension de la méthode de substitution pour tenir compte de la présence de trous dans le couvert, notamment les espaces et les interstices.

BACKGROUND

The last decade was the scene of a major shift in the way scientists analyze the forest, that placed greater emphasis on the individual tree rather than on the stand as the primary spatial unit of interest. This was due, in part, to the emergence of new scientific research issues in thematic mapping, such as the spectral analysis of individual tree crown architecture resulting from the availability of high resolution remote sensors. This shift was also related to the need for developing robust multi-scale spatial validation methods for individual-based dynamic models of forest succession (Shugart, 1984; Coquillard and Hill, 1997; Deutschman, 1997).

Recently, several methods have been developed to achieve individual tree delineation from high resolution imagery, which include peak filters, iterative windows-based variance analysis and valley tracing algorithms (Gougeon, 1995; Hay et al., 1996, 1997). While these methods show interesting results, such methods present two main limitations. First, their efficiency is proven almost exclusively within the context of conifer cover types. Intuitively, we can expect a relative success of these methods for deciduous cover in low density stands, given the presence of discrete tree crowns. However, this success can be expected to decrease significantly in high density cover due to an increase in the fuzziness inherent to high density deciduous crown boundaries. Figure 1 illustrates this phenomenon. A simple digital photo-interpretation experiment was made on a small mixed forest experimental plot near Quebec City, by ten photo-interpreters. In this image we clearly see the uncertainty at the frontiers of the delineated crowns, which relates to both the inter- and intra-analyst inconsistency (Edwards and Lowell, 1995). It is also important to consider that crown frontiers may be fuzzy by nature in specific situations and at a varying scales of observation. Consequently, an automated crown identification algorithm should allow for error quantification of such data according to their fuzzy nature.

Second, these methods suppose the availability of remote sensing imagery over a whole study area. However, the reality is that scientists often use multi-source datasets, focusing on information that is quickly available for the region of interest (i.e., GPS tree locations, aerial photos, high resolution hyperspectral imagery, etc.). These kind of data usually provide a considerable amount of heterogeneous information with different degrees of generalization. Consequently, such datasets require the availability of a methodology to manage, or quantify, this differential uncertainty or 'fuzziness'.

We suggest that an alternative to both problems would be to define a fuzzy interpolation method that is adaptive to the natural structure of the forest and to the types of available data. Such fuzzy logic applications began with the work of Lowell (1994) on forest stand interpolation using punctual photo-interpreted data. Much of Lowell's work is based on previous research conducted by Gold (1989, 1991) on natural spatial adjacency using Voronoi diagrams, and his ideas on the development of a spatial interpolation method called *the theft*. This method has several advantages over classical interpolation methods. First, it avoids arbitrarily choosing the number and the location of the neighbours considered in the interpolation, and it avoids selecting an arbitrary distance based weighting function. Another advantage is that it allows for the use of linear, polygonal, and punctual source data, without under- or over-estimation of their specific influence within the interpolated results. This natural approach was first developed for meso-scale applications, i.e., DEM and stand interpolation. It was also applied for specific density interpolation considering spatial adjacency of individual stems (Eldridge and Edwards, 1993). However, this study was tested under a conifer cover without taking into account the possible presence of non-vegetation structures in the canopy.

STUDY AREA AND DATASET

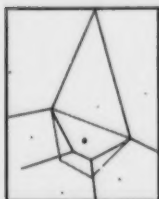
Our study area is the Muirs forest located at the northern edge of the temperate deciduous forest in the southwestern part of the Province of Quebec. This small piece of old-growth forest covers 11 ha and is codominated by *Acer saccharum* and *Fagus grandifolia*. Within this area, data from two scenes of 575 m² (each) are used for analysis. The Muirs forest database includes extensive information for every individual tree in the area, such as the systematic x, y location of each individual stem (living trees and dead individuals), DBH, decomposition state of dead trees, and taxonomic identification at the species level.

MATERIAL AND METHODOLOGY

The methodology is subdivided into four steps. First, the theft interpolation algorithm was coded in C language using the GIS GRASS4.1 environment. Next, we integrated the Muirs forest database into GRASS raster files using a 20 cm spatial resolution. This choice was made to find a compromise between the time needed to interpolate the two scenes and an acceptable representation of the crowns. The study area was partitioned using Voronoi diagrams, and the trunk location of the trees belonging to the canopy layer was used as Thiessen polygons centroids. Fuzzy interpolation of individual crowns was performed using the theft method, taking into account the local structure of the canopy. Finally, a global characterization of the fuzziness in the dataset was performed.

CONVENTIONAL FUZZY AREA STEALING INTERPOLATION

This interpolation procedure consists of a fuzzy measure of the uncertainty (or the certainty) that a pixel belonging to a universe U also belongs to a subset T . In this case, T is a specific taxon, but it could also be a specific individual. A membership index is assigned for every pixel based on the area the Thiessen polygon associated to the interpolated pixel steals from its natural neighbors - for every taxon considered. Applying Lowell's approach, we can formalize a membership function in this form:



$$\mu_{(t)} = \frac{\beta_{(t)}}{\sum_{n=t} \beta_{(n)}} \quad (1)$$

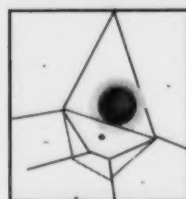
Figure 2. Example of area stolen from the natural neighbours of a Thiessen polygon associated to an interpolated pixel (adapted from Lowell, 1994).

μ is the membership index and β is a specific stolen area. Such a function is most appropriate for closed deciduous canopy interpolation, where uncertainty can be considered as null at a Thiessen polygon centroid (the apex), but increases towards its borders, taking into account the shape of the Thiessen polygon and the adjacency of its natural neighbours. However, high density covers are not always totally closed and often contain holes. In this study, the conventional fuzzy theft algorithm is then modified to take into account two subsets of holes: interstices and gaps.

INTERSTITIAL SITUATION

We call interstice a discrete hole in the canopy that has no physical descriptor (i.e., point, line or polygon) in the dataset. Typically, an interstice would be smaller than the smallest gap resulting from a tree death. It could be created by different aged individuals in a stand, epidemics, partial gap reinvasion by natural neighbors, etc.

A generic way to define a membership function that could manage interstitial situations would be to take into account specific genetic crown expansion limitations as the maximum possible crown diameter (MPCD) of an individual. In this study, we apply this approach to the Thiessen polygons dominated by the taxon *Tsuga canadensis* for which the maximum possible crown diameter is fixed at six meters (Millet, personal communication). Figure 2 illustrates this approach for the situation where the interpolated pixel is not included in the area covered by this maximum possible crown diameter.



$$\mu_{(t)} = \frac{\beta_{(t)}}{\sum_{n=t} \beta_{(n)}} \quad \mu_{(i)} = \frac{\beta_{(i)}}{\sum_{n=t} \beta_{(n)}} \quad (2)$$

Figure 3. Modelling of the distance from the apex to the maximum possible crown diameter of a specific individual. Here the interpolated pixel is located outside this diameter.

In the situation where a pixel is included in the area of MPCD, it belongs to a higher belief domain characterized by a membership threshold at the MPCD border. This function should then include a term that weights the membership index by a normalized distance (d) from the maximum possible border to the centroid

of the Thiessen polygon (Equation 3). The constant δ represents the empirical belief that a pixel located at the MPCD border belongs to the individual. This value could be obtained by empirical observation of the distribution describing the frequency of mature individuals that reach this maximum diameter for a particular species in the field. Here we make the assumption that this situation leads to an equal chance of belonging to the state interstice or to the individual modelled by the polygon.

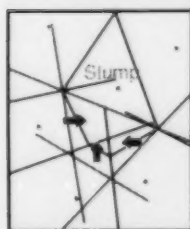


$$\mu_{(i)} = (\delta + d \cdot (1 - \delta)) \cdot \left(\frac{(\beta_{(i)} + \beta_{(i)})}{\sum_{n=1}^{n=not+i} \beta_{(n)}} \right) \quad \mu_{(i)} = \left(\frac{(\beta_{(i)} + \beta_{(i)})}{\sum_{n=1}^{n=not+i} \beta_{(n)}} \right) - \mu_{(i)} \quad (3)$$

Figure 4. Same situation as in Figure 3. The interpolated pixel is located within the possible crown diameter area.

GAPS SITUATION

In this study, we define a gap as a hole in the canopy that has a meta-descriptor in a given dataset. Gaps can be represented in a spatial database in three main ways. The first is when available data include the discrete delineation of a particular gap by polygon boundaries (usually by photo-interpretation). This kind of data can be handled with a high degree of certainty and should be included in the Voronoi tessellation, avoiding the area stealing computation. The second situation occurs when gaps are represented in a dataset by their centroid. The fuzzy interpolation should then be computed using the same function as for the trees. The last situation considered here is when the gaps are represented in a dataset by the point location of dead trees at the ground level. Given the case that death date or decomposition state are *a priori* available within the dataset, the fuzzy interpolation could be weighted to model the progressive re-invasion of the neighbors into the gap. The membership function then includes a weighting term that represents the degree of canopy openness according to the particular temporal state of a gap. Such an index is derived from empirical measures for the set of species present in a specific study area. Here we are using a canopy openness index defined by Walter and Torquebiau (1997) to produce a membership function illustrated by equation 4. The parameter represents this index for a specific gap state. This index suggests a mean canopy openness of ~0.60 in situations of recent a gap, ~0.15 for a transition zone and ~0.05 for a near closed canopy.



$$\mu_{(i)} = \frac{\beta_{(i)} + (1 - \alpha_{(e)}) \cdot \beta_{(g)}}{\sum_{n=1}^{n=not} \beta_{(n)} + \beta_{(g)}} \quad \mu_{(g)} = \frac{\alpha_{(e)} \cdot \beta_{(g)}}{\sum_{n=1}^{n=not} \beta_{(n)} + \beta_{(g)}} \quad (4)$$

Figure 5. Modelling a gap reinvansion by natural neighbours according to the state of the gap.

FUZZYNESS MONITORING

The interpolation algorithm generates a set of interpolated layers that represent the relative belief that a single pixel belongs to a particular taxon for the case of interstitial modelling and to a specific individual for the case of gap modelling. A simple variance measure is then performed on these layers to produce a global measure of the degree of fuzzyness of the taxa modelled in the study area.

RESULTS

The graphical output of the results are presented at the end of this paper. Figure 6 illustrates the Voronoi tessellation in the study area. Figures 7 to 11 show the interpolation results for Lowell's method for every taxa considered in the first study area. Numeric values represent the membership index (0..1) for *Acer saccharum*, *Fagus grandifolia*, *Ostrya virginiana*, *Tilia americana* and *Tsuga canadensis*, respectively.

Figure 12 represents the maximum possible crown diameter for *Tsuga canadensis*. Each color (grey tone) of the buffer analysis represents a single pixel distance unit. Note that the MPCD modelling is restricted to the area dominated by a single individual (i.e., the Thiessen polygon) in order to preserve the integrity of the area of influence associated to the other individuals in the neighborhood. This figure clearly shows that three of the four individuals present in the scene exhibit a possible interstitial context. Figures 13 and 14 show the result of the interpolation taking into account this possibility. Qualitative observation suggests that this procedure creates a much more realistic degree of membership distribution than the conventional method (Figure 11). We can see a high possibility for the presence of an interstice outside the MPCD. On the other hand, the same procedure also enhances the possibility of an interstitial presence into the MPCD area, but at a lower level. Furthermore, it is interesting to note that the spatial gradient of the membership indexes inside the MPCD flow in an opposite direction than the pixels outside. This situation in itself constitutes an algorithmic validation of the interstices modelling. Finally, it is important to note that the basic property of the conventional (Theft) method that guarantees a total membership index to the individual at the apex location is also preserved by this extension of the method.

Figure 15 illustrates the variance analysis of the taxonomic fuzzy interpolated layers obtained in the first study area. Bright values represent areas of low variance while dark values illustrate high variance among the fuzzy layers, for every pixel interpolated. Low variance pixels represent areas where the membership indexes are very close to each other, suggesting a high degree of fuzzyness in the dataset. On the other hand, high variance areas suggest much more certainty among the dataset, and a higher belief that the data at these locations are accurate. We remark an anisotropic tendency towards the frontiers of the Thiessen polygons. This phenomenon is driven by the distributional and the morphometric variability of those polygons - which relates back to the genetic characteristics of the individual trees, i.e., competition for resources etc.

Figures 16-22 represent the results of the conventional fuzzy area stealing interpolation in the second study area. Each layer illustrates the belief that a specific pixel belongs to a given individual. Figure 16 shows the membership indexes for the gap situated at the center of the scene. This gap state is described in the dataset by the presence of a stump which means that the gap is in a transition state. Figures 23 to 29 represent the results of the interpolation taking into account the state of the gap according to equation 4. As shown in figure 23, this process significantly reduced the membership of the interpolated pixels to the state gap. On the other hand, Figures 24 to 29 show an anisotropic increase in membership indexes for the gap's first order natural neighbours. Note that the sum of the neighbouring trees membership values inside the gap's Thiessen polygon can be greater than one. Such values not only reflect the possible invasion of those different neighbours into the gap according to their stolen area, but also the fact that it can be highly possible to find the presence of every natural neighbour in the gap area.

CONCLUDING REMARKS

This study addresses the problem of developing an adaptive interpolation procedure for tree crown quantification and characterization in a high density deciduous/mixed cover context. Fuzzy sets theory ——— proposes a structural description of the world that is closer to reality and does not reject the presence of certainty elements. It allows us to simultaneously negotiate with structures characterized by sharp frontiers in space, as well as with uncertain data, thus providing a higher quality of information to the scientists.

Combining this approach with the theft interpolation method allows for the generation of multiple fuzzy layers for every taxa/individual in a particular scene on the basis of bole/apex location. Qualitative observation of the results suggests that the application of this approach leads to realistic output in a closed canopy.

However, we have also shown that this method has limitations when holes are present in a canopy, namely interstices and gaps. In the presence of interstices, the use of complementary data provides a major improvement over the classic method. When available, the use of Thiessen polygons taxonomic attributes and more specific data - like the maximum possible crown diameter - can lead to more realistic results. We have also illustrated that the modelling of gap structure may be improved by fuzzy logic. It allows the user to handle the fact that a specific pixel might belong to different taxa with a sum of its membership degree that could be greater than 1, thus illustrating that a gap could be reinvaded by different taxa at the same time, with a high degree of possibility.

We have also illustrated the potential of our approach as a global fuzziness monitor in a specific dataset using variance overlay measures of specific fuzzy layers. The use of such global indexes could be very useful for researchers to visually quantify spatial uncertainty in their dataset.

This study constitutes the first application of our extensions to the Theft method made in the Muirs forest which represents an exceptional quality of information. In the future, the described methodology will be applied and validated on a more realistic site: the Duchesnay forest in the area of Quebec city. Here, the location of each tree will be achieved using digital stereoscopy, field validation, and peak filters, and taxonomic attributes will be further evaluated using spectral unmixing models. At another level, more research will be done concerning the best way to model gaps. The emphasis will be on the development of a more generalized algorithm that will be species dependent and that will take into account the date of data acquisition for modelling the vegetation's temporal dynamics within gaps in a given local. The influence of the resolution on the interpolation results will also be investigated. It will also be interesting to define and include necessity measures related to the direction and to the magnitude of specific events such as the extension rate of a specific crown. This should ultimately lead to much more refined belief measures. Considering that fuzzy measures give fuzzy results, fuzzy inferences and data defuzzification processes will also be at the center of our research interests.

ACKNOWLEDGMENTS

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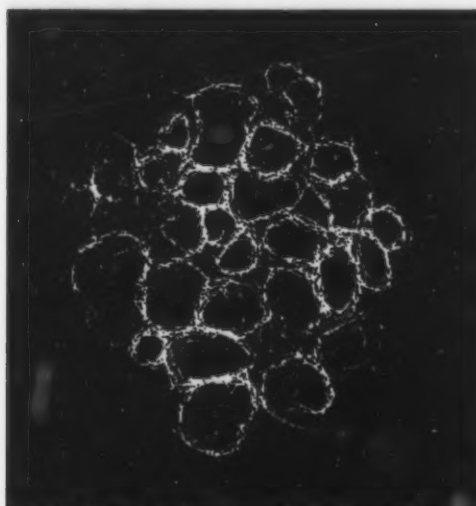


Figure 1. Manual deciduous crown delineation experiment made by ten photo-interpreters using a digital stereoscope. This suggests a fuzzy natural structure in high density deciduous canopy.

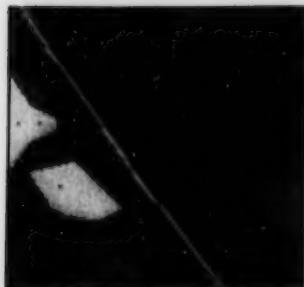


Figure 6. Voronoi tessellation in each color represents a particular species.

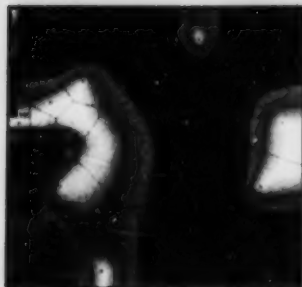


Figure 7. Membership layer for the taxon *Acer saccharum* using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

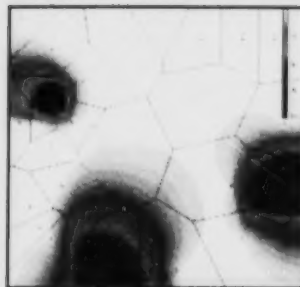


Figure 8. Membership layer for the scene 1 taxon *Fagus grandifolia* using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

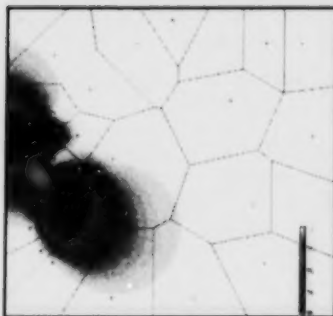


Figure 9. Membership layer for the taxon *Ostrya Virginiana* using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

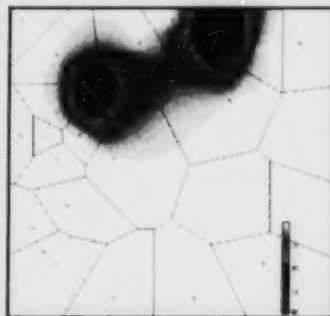


Figure 10. Membership layer for the taxon *Tilia americana* using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

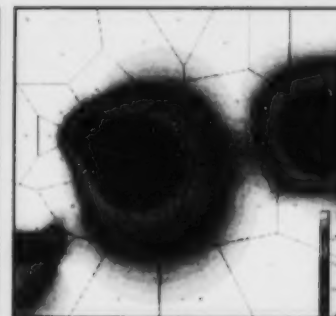


Figure 11. Membership layer for the taxon *Tsuga canadensis* using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

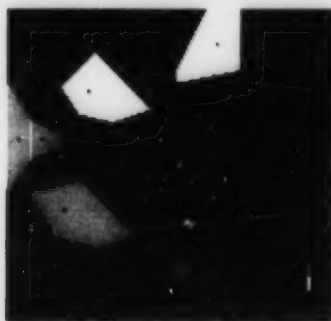


Figure 12. The source layer for the modelling of interstices. This takes into account the Voronoi tessellation and the MPCD of the taxon *Tsuga canadensis*. Buffer values are one pixel wide.

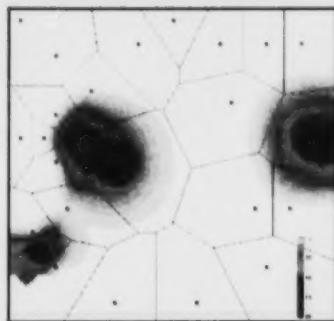


Figure 13. Membership layer for the taxon *Tsuga canadensis* taking into account the MPCD. Values are ranging from 0 to 1

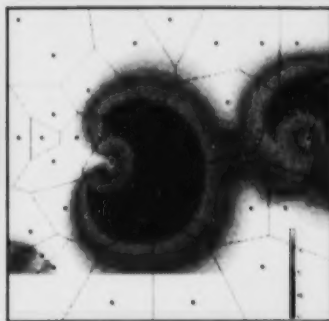


Figure 14. Membership layer for the state interstice taking into account the MPCD of *Tsuga canadensis*. Values are ranging from 0 to 1.

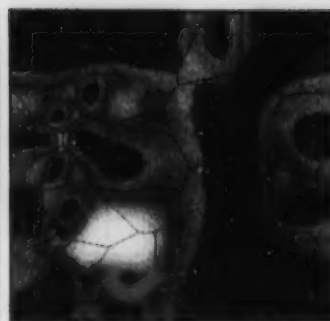


Figure 15. Variance measure of the membership layers (scene 1) showing the global taxonomic fuzzyness in the dataset.

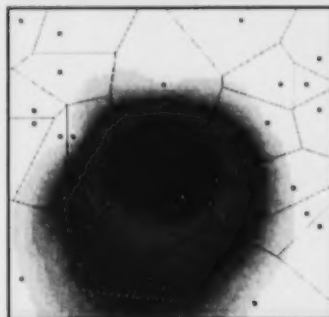


Figure 16. Membership layer to the gap using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

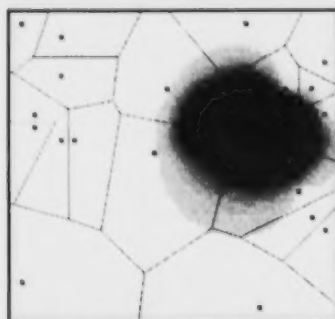


Figure 17. Membership layer for the neighbouring tree 1 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

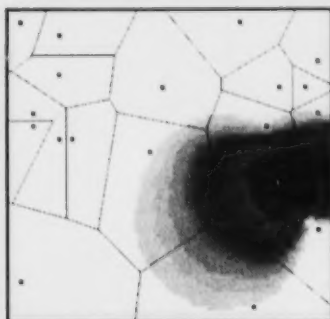


Figure 18. Membership layer for the neighbouring tree 2 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

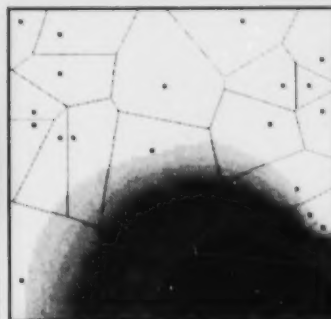


Figure 19. Membership layer for the neighbouring tree 3 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

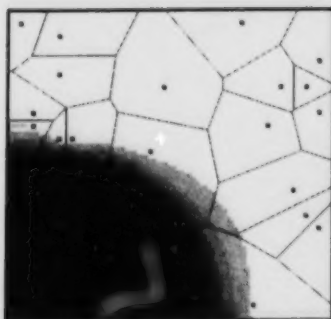


Figure 20. Membership layer for the neighbouring tree 4 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

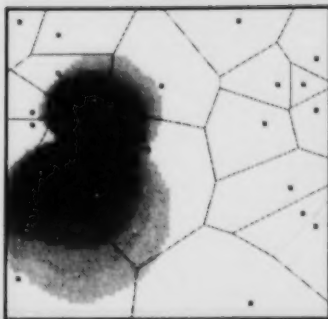


Figure 21. Membership layer for the neighbouring tree 5 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

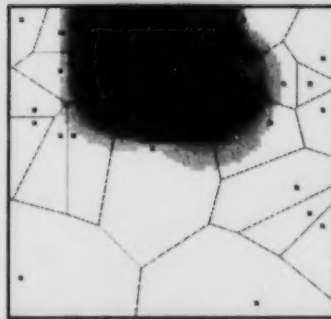


Figure 22. Membership layer for the neighbouring tree 6 using the conventional fuzzy area stealing method. Values are ranging from 0 to 1.

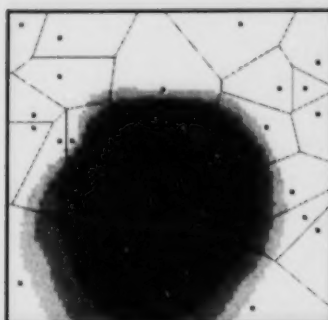


Figure 23. Membership layer to the gap using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 0.15.

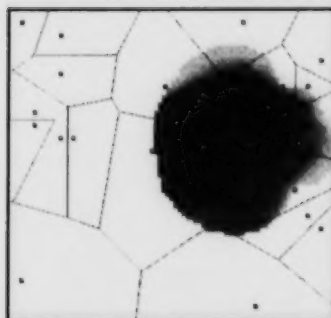


Figure 24. Membership layer for the neighbouring tree 1 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

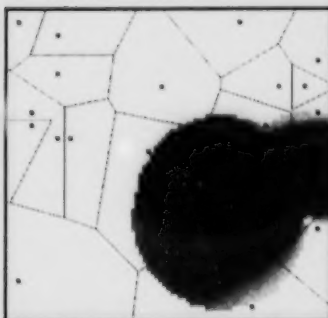


Figure 25. Membership layer for the neighbouring tree 2 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

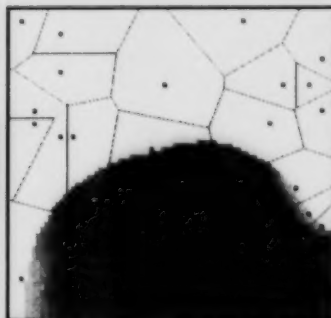


Figure 26. Membership layer for the neighbouring tree 3 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

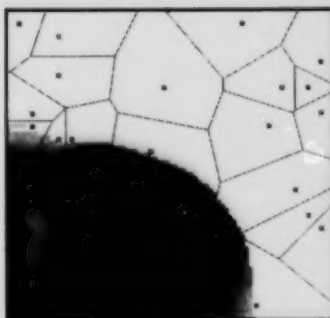


Figure 27. Membership layer for the neighbouring tree 4 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

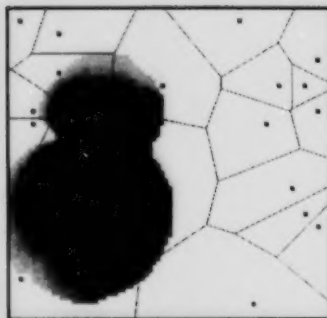


Figure 28. Membership layer for the neighbouring tree 5 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

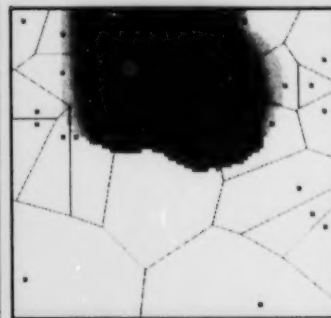


Figure 29. Membership layer for the neighbouring tree 6 using the fuzzy area stealing method and taking into account the state of the gap. Values are ranging from 0 to 1.

TREE ISOLATION AND SPECIES CLASSIFICATION

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ABSTRACT

To achieve a fully automated forest inventory based on high resolution color infrared aerial images, two major digital image analysis tasks have to be solved: tree isolation, and tree species classification. A prototype software system capable of the following functionality has been developed and implemented in 1985-1988:

- 1) Isolation of individual trees in dense forest stands by a Vision Expert System, and
- 2) Recognition of the tree species by a neural network.

This work is reviewed pointing out advantages and disadvantages of the approach. An important issue is how to cope with the question of different spatial extensions of the objects (i.e., spatial scale). New experiments show that scale space theory is well applicable. However, due to the very complex nature of the problem, any successful tree recognition system will require to model and to use additional expert knowledge.

Keywords: tree recognition, species classification, vision expert system, neural network, scale space.

RÉSUMÉ

CIRCONSCRIPTION DES ARBRES ET CLASSIFICATION DES ESPÈCES

Pour réaliser un inventaire forestier entièrement automatisé, à partir d'images aériennes infrarouges couleur à haute résolution, il faut accomplir deux principales tâches d'analyse numérique d'image : la circonscription des arbres et la classification des espèces. Entre 1985 et 1988, on a mis au point un logiciel prototype comportant les fonctionnalités suivantes :

- 1) la circonscription des arbres dans des peuplements denses par un système expert de vision;
- 2) la reconnaissance des espèces d'arbres à l'aide d'un réseau neuronal.

Le présent mémoire porte sur l'étude de ces travaux en indiquant les avantages et les inconvénients de la méthode. On se penche particulièrement sur les moyens à prendre pour tenir compte de la question des diverses extensions spatiales des objets (échelle spatiale). Les nouvelles expériences indiquent que la théorie de l'échelle spatiale convient très bien. Cependant, en raison de la nature extrêmement complexe du problème, le système d'identification des arbres nécessitera la modélisation et l'utilisation de connaissance experte additionnelle.

INTRODUCTION

In the mid 80's, a new Austrian forest inventory system has been implemented which is partly based on the visual interpretation of color infrared aerial images. An overview of this inventory system is given in a

companion paper in the same proceedings (Pinz, 1998). Essential steps in the visual interpretation which still hinder the complete automation of the whole process are the tree recognition and isolation and the tree species classification. Research in this direction has led to the development of a hybrid system. A 'Vision Expert System' VES (Pinz, 1988, 1989, 1991) is responsible for tree finding and crown radius estimation, while a neural network (Pinz and Bischof, 1990, 1992; Pinz et al., 1993) is trained to recognize tree species. Most of this research was performed between 1983-1989 at the University of Agriculture and Natural Resources in Vienna within the framework of two major research grants. This paper reviews this work as well as at pointing out problems. In addition, a few new experiments put the problem of finding trees of varying sizes at different spatial resolutions in the framework of scale space theory in computer vision (Lindeberg, 1994).

Throughout this paper, tree recognition and species classification will be discussed based on the following assumptions:

- Input images are high resolution digital images of high resolution color infrared aerial images, e.g. approximately 10 cm pixel size on ground in the case of Figure 1a.
- Only locations in the center of an aerial image are observed, so that a 2D blob model will be well suited for a crown, avoiding geometrical distortions and difficult illumination effects at the periphery.
- Solutions for dense forest areas are presented. Methods will be unreliable at the border of a forest and in cases where trees are sparsely covering the ground.
- A pure 2D approach relying on information from a single image is presented.

TREE FINDING AND DELINEATION

The Vision Expert System reviewed in this section was originally designed as a general purpose expert system for image interpretation in remote sensing. It was composed of the following hard- and software components:

- A Lisp-based software system with a multilevel knowledge representation (rules, frames, attached procedural knowledge),
- A host computer with libraries and interfaces to control special purpose image processing hardware,
- Special purpose image processing hard- and software.

There are other comparable architectures described in the literature, for instance, the Umass VISIONS and schema system (Draper et al., 1989). The original KBVision™ system was designed in a similar manner, containing a high level knowledge module in Lisp. The proposed Image Understanding Environment IUE (Kohl and Mundy, 1994) was also planned to be implemented in both C++ and Lisp. There is a major advantage of such an architecture: depending on the kind of the problem and on the level of reasoning, the user is able to implement the required components using the tool suited best. For our VES implementation this means that high level reasoning about the appearance of trees as well as about applicable methods was implemented in Lisp rules, specific knowledge about objects (trees, roads, blobs, lines, etc) was stored in FRL frames (Minsky, 1975; Roberts and Goldstein, 1977), and image processing tasks were implemented based on standard libraries and in Pascal code.

The goal of VES was to locate the center of a crown, to estimate the crown radius, and to reliably repeat this processing for all trees in the image. To give an example for this task think of Figure 1a being the current input image 'Find tree' was the corresponding Lisp command entered at the top level of the system. This command started the fully automatic invocation and iteration of several methods. Processing was terminated when all objects were found (i.e., further iteration would not provide better results). The final result of the processing is visualized by Figure 1d. A more detailed description of the main processes involved is given below.

Figure 2 gives an overview of the key concept in VES - its object representation in frames. We distinguish between objects in the scene (categories A and C: trees, roads, etc.) and corresponding objects in the image (categories B and D: blobs, lines, etc.), and between generic objects (categories A and B: general knowledge

about the objects, supposed appearance, etc.) and individual objects (categories C and D: specific instances with specific attributes like position and radius). Figure 5 presents a more detailed diagram including a hierarchy of several levels of abstraction (scene object – tree – spruce). Please note the explicit relations "represents" and represented by which enable the reasoning between objects in the scene and their expected appearance in the image. The Lisp notation in Figure 2 and Figure 5 is Frame Representation Language FRL (Roberts and Goldstein, 1977). A Lisp-based system reasoning with frames today would probably use the Common Lisp Object System CLOS.

Figure 3 sketches the reasoning processes in VES based on the representation scheme described above. The system starts searching for a scene object. This search is projected onto the image domain and leads to a search for the corresponding image object. Image objects can then be found by several methods (i.e., application of several sequences of image processing algorithms). One specific method for finding compact bright blobs and estimating their radius is described below. Finding an image object leads to the generation of a hypothesis for a corresponding scene object. The complete reasoning process can be either repeated in an identical manner to find more scene objects or parameters can be tuned. VES will try to resolve conflicts (e.g., trees standing too close) or try to invoke other methods for scene object finding when the result is unsatisfactory (e.g., large regions in the image without any interpretation result).

Figures 1 and 4 illustrate the processes involved in the iterative refinement of a scene interpretation in terms of trees. The crown of a tree in dense forest will appear brighter than the surrounding background. Tree finding can therefore be done by searching for local brightness maxima in the image. While the high spatial resolution of the input image is required for several processing steps (estimation of the crown radius, assessment and verification of results), a process looking for local brightness maxima in the original image would find all the fine spatial details provided there (e.g., several maxima on a single branch of a tree). It is therefore necessary to smooth the input image by lowpass filtering. Making use of the special purpose image processing hardware with a very fast convolver, smoothing in VES could be achieved by implementing local averaging operations with rather large window sizes. Figure 1b shows the result of smoothing Figure 1a with a 25×25 averaging kernel. Now, only 54 local brightness maxima have survived as shown by Figure 1c. It is obvious, that a single lowpass filter will not be able to deal with all possible scales occurring in an image, e.g., for trees of rather different sizes or crown structures. Parameter variations (in this case variations of the size of the kernel) solve this problem. Several different kernel sizes yield different brightness maxima. (There are more maxima for smoothing with smaller kernels and fewer maxima for smoothing with larger kernels and the position of the maxima varies slightly. This step is not illustrated in Figure 1.) After a combination of significant maxima from all scales we end up with a set of candidates for crown center positions. Since the system is at this time reasoning in the image domain, it reasons in term of candidates for blob centers. Not each of these candidates will necessarily mark a sufficiently significant compact image blob, nor can it be taken for sure that each blob represents a crown of a tree. Thus, several verification steps are required.

Verification of blob compactness and significance is obtained at the image level. We go back to the original spatial resolution and calculate 'radial brightness distributions' for each blob candidate (Figure 4). Following concentric circles and averaging the greyvalue found along each circle yields a diagram of mean greyvalue / radius. A 'good' candidate for a significant blob should show a behavior like in Figure 4. Within a radius of reasonable size (the size can be calculated from a threshold for maximum crown radius) the mean greyvalue has to drop below a threshold. For the example in Figure 1d, this threshold was set to 50% of the maximum. After this first verification step at the image level we end up with bright blobs which might represent the crown of a tree. Further verification steps at the scene level include reasoning about spatial relations between trees and between trees and other objects (e.g., trees standing too close, tree growing in the middle of a road).

As a final result of the vision expert system VES, trees are obtained as 'scene objects'. Each tree is represented as an individual object in its own FRL-frame, and several further reasoning steps could be performed at scene level. In terms of image interpretation, VES returns

- image coordinates which are very likely to be positioned on top of tree crowns, and
- estimates for the crown radii.

TREE SPECIES RECOGNITION

The VES output described above (crown position and crown radius) is fed into a neural network for tree species classification. A rather simple and straightforward approach was implemented using a fully connected 3 layer feedforward neural network trained with error backpropagation (Pinz and Bischof, 1990). Such an approach can be used because we already have constrained our classification problem to a case of a rather compact image object with known location (see also Pinz et al., 1993). Figure 6 shows the architecture of our network. 450 input units directly represent pixel greyvalues of an area of 15×15 pixels taken from 2 spectral channels of the aerial image. Since the blue channel of a color infrared aerial image is strongly correlated with the green one, it is sufficient to use only two spectral channels as input (green and red). A further 30 input units feed the locally coded radius into the network.

The input image is preprocessed by contrast enhancement transforming the original range of greyvalues to an interval of $[-0.5..0.5]$. A nonlinear sigmoid function provides further contrast enhancement in the middle range. A series of experiments showed that 13 hidden units are best suited to cope with 480 input units and the goal of distinguishing between five different tree species. The output of the network is coded locally, with one output unit for each species. An extension of this originally used architecture showed advantages of a sixth output unit to represent unknown objects (rejection class).

Many experiments were carried out with this and with similar network architectures and with training and test sets of varying complexity. Overall results were approximately 85% correctly classified tree species on the training and on the test sets. Significant improvements were achieved by a new method termed 'neural network surgery' (Pinz and Bischof, 1992), ending up with the best performance of 93% for the training set and 90% for the test set.

TREE DETECTION IN LINEAR SCALE SPACE

Scale plays a central role in the VES approach to tree detection described in section 2. Recently developed notion of scale space theory in computer vision puts the above arguments about scale, sizes of smoothing kernels, etc. on a solid theoretical basis (Witkin, 1983; Koenderink, 1984; Florack et al., 1992; Lindeberg, 1994; ter Haar Romeny, 1994). In this section, new results for blob detection based on automatic scale selection are presented.

For any N -dimensional image $f: \mathbb{R}^N \rightarrow \mathbb{R}$, its scale space representation $L: \mathbb{R}^N \times \mathbb{R}_+ \rightarrow \mathbb{R}$ is defined by

$$L(\bullet; t) = g(\bullet; t) * f(\bullet)$$

where $g: \mathbb{R}^N \times \mathbb{R}_+ \rightarrow \mathbb{R}$ denotes the N -dimensional Gaussian kernel and the variance $t \in \mathbb{R}_+$ of the Gaussian kernel is called the scale parameter. Based on this representation, scale space derivatives are defined by

$$L_{x^i a}(\bullet; t) = \partial_{x^1} a^1 \dots \partial_{x^N} a^N L(\bullet; t) = (\partial_{x^1} a^1 \dots \partial_{x^N} a^N g(\bullet; t)) * f(\bullet)$$

with corresponding normalized derivatives $\partial_{\xi_i}^n = t^{n/2} \partial_{x_i}^n$ where ξ represents the normalized coordinate corresponding to the variable x and n denotes the order of differentiation.

In terms of this framework, a large number of feature detectors can be formulated as (linear and nonlinear) combinations of partial derivatives. Specifically, scale levels for feature detection can be selected by detecting local extrema over scales of such differential geometric descriptors (Lindeberg, 1993, 1994, 1996). Assuming a blob-like structure, trees in aerial images can be detected from points which are simultaneously maximal with respect to space and scales in the normalized Laplacian $-\Delta L_{\text{norm}} = -t \Delta L$. To rank these features by significance, we multiply the normalized response ΔL_{norm} at each scale space maximum by a factor of $t^{1/2}$, which gives the following significance measure $S(A)$ for each scale space extremum:

$$S(A) = -t^{1/2} \Delta L_{\text{norm}}(x, y).$$

Furthermore, to suppress overlapping features, any scale space maximum A is rejected if there exists any scale space extremum B such that

$$\text{center}(A) \in \text{support region}(B) \wedge \text{center}(B) \in \text{support region}(A) \wedge t_A/t_B \in [1/\alpha, \alpha] \\ \alpha > 1, \quad S(A) < S(B)$$

where we have chosen $\alpha = 4$, corresponding to a ratio of 2 between the blob radii.

Figure 7 shows results of this blob detection approach to the same image which demonstrated blob finding with VES (Figure 1a). The remaining examples (Figure 8-12) are all based on the image in Figure 8, with Figures 10-12 showing different portions of Figure 8 (trees of different sizes and species).

These examples are first results obtained by applying the scale space approach sketched above to our problem of tree finding in high resolution aerial images. Results are quite comparable to the results achieved for pure blob detection by VES 10 years ago. However, the scale space approach is better formalized, understandable, and reproducible. Results shown in Figure 8-12 clearly demonstrate the requirements for high level reasoning and several pre- and postprocessing steps, probably in a similar way as in VES.

DISCUSSION

The main purpose of this paper has been to give a review of techniques developed more than 10 years ago within the Austrian forest inventory program. It is our impression that correct and reliable tree isolation and tree species classification still are a very demanding task. Approaches presented here can only qualify as a prototype implementation and much work would still be required to build a fully automatic system for operational use. However, several statements should hold with sufficient generality:

- No single algorithm is able to solve the complete task of tree finding and species classification. A hybrid multilevel approach to scene interpretation, where several competing hypotheses are established and evaluated is required.
- For many interpretation tasks it will be sufficient to find the center of the crown and to provide an area in its surrounding, which definitely belongs to the same tree. Our proposed method of compact blob detection seems well suited. It is not necessary (and it is extremely difficult) to exactly delineate each crown.
- Scale constitutes a central problem in the whole task. A fully automated system should be able to recognize trees of considerably different sizes, as well as to automatically recognize changes in image scale. Scale space theory presents a well established mathematical formalism. Experiments presented in this paper demonstrate the benefits of the method.
- Our experiments with neural networks for species recognition have shown very high classification accuracy above 90%. However, these experiments were based solely on images from the Austrian forest inventory. General applicability of the method for other populations, e.g., in Canadian forest, has still to be shown.

ACKNOWLEDGEMENTS

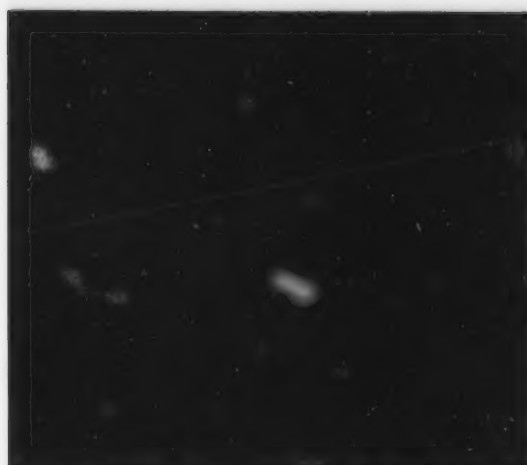
I wish to thank Klaus Wiltshi for his help with the section on linear scale space and for help with the scale space experiments. Work reported here was originally supported by the Austrian Ministry of Agriculture and Forestry "BMLF Projekt Österreichische Waldzustandserhebung mittels Methoden der Waldzustandsinventur" and by the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung (FWF) Forschungsschwerpunkt Fernerkundung".

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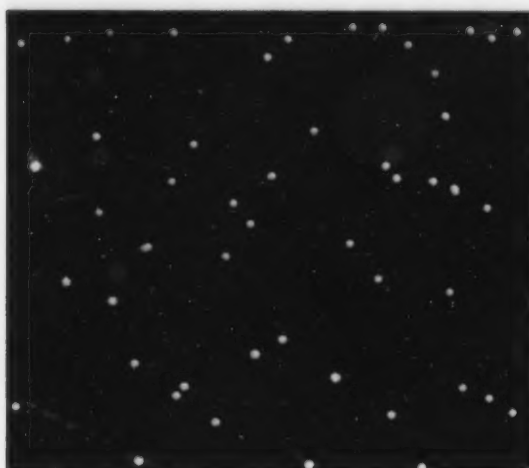
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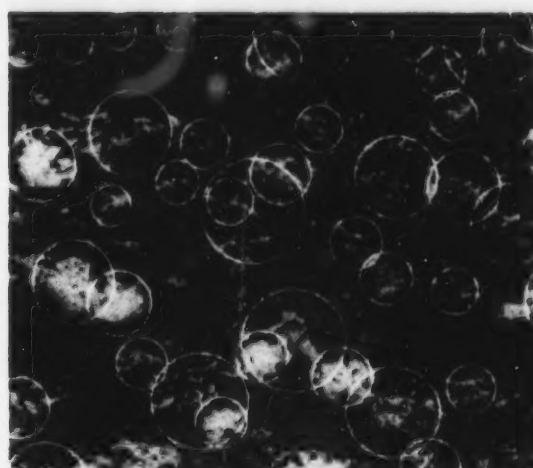
(a) Original image. Aerial scale of 1:4000 was digitized with 25 μm pixel size resulting in a true pixel size of ≈ 10 cm in the scene.



(b) Original image smoothed by convolution with a 25 x 25 averaging kernel.



(c) Local maxima detected in the smoothed image.



(d) Image objects (circular blobs) found and superimposed on the original image.

Figure 1. VES finds candidate image objects (circles) representing trees in the scene by searching for bright blobs in the image.

A	scene objects OBSC	image objects OBIM	B
	(AKO (\$VALUE (OBSC))) (CLASSIFICATION (\$VALUE (GENERIC)))	(AKO (\$VALUE (OBIM))) (CLASSIFICATION (\$VALUE (INDIVIDUAL)))	
	generic objects		
	individual objects		
	(AKO (\$VALUE (OBSC))) (CLASSIFICATION (\$VALUE (INDIVIDUAL)))	(AKO (\$VALUE (OBIM))) (CLASSIFICATION (\$VALUE (INDIVIDUAL)))	
C			D

Figure 2. General scheme of object representation used by VES.

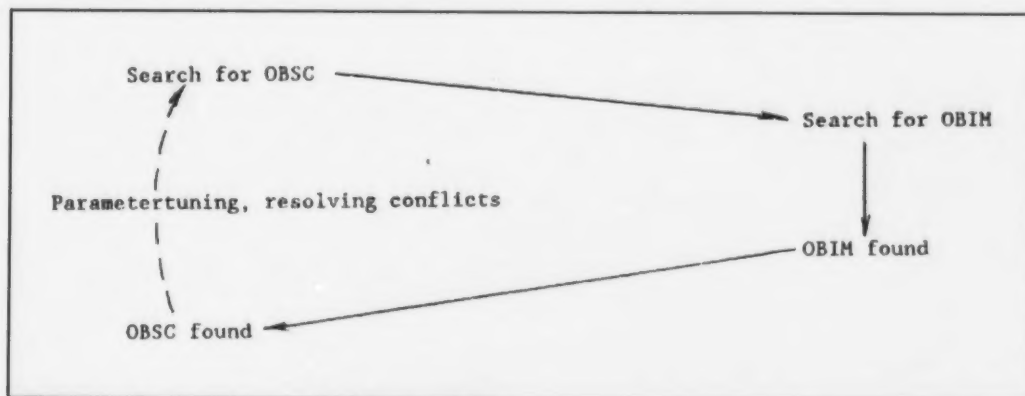


Figure 3. The general processing scheme of VES.

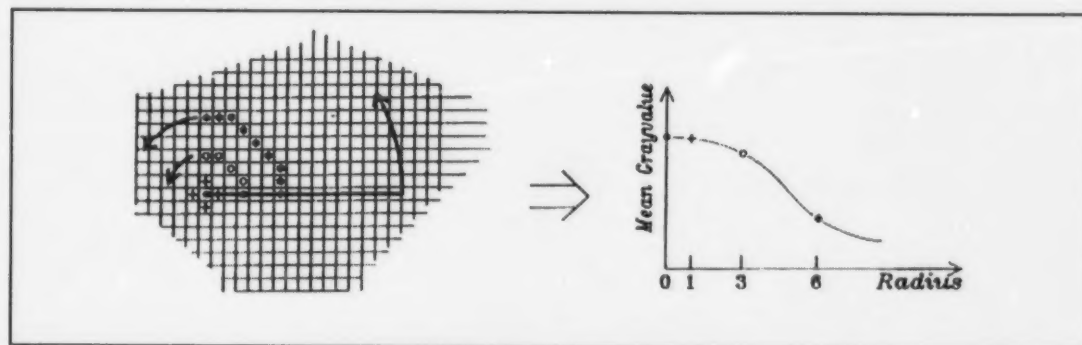


Figure 4. A projection method called radial brightness distribution to estimate the radius of a bright blob.

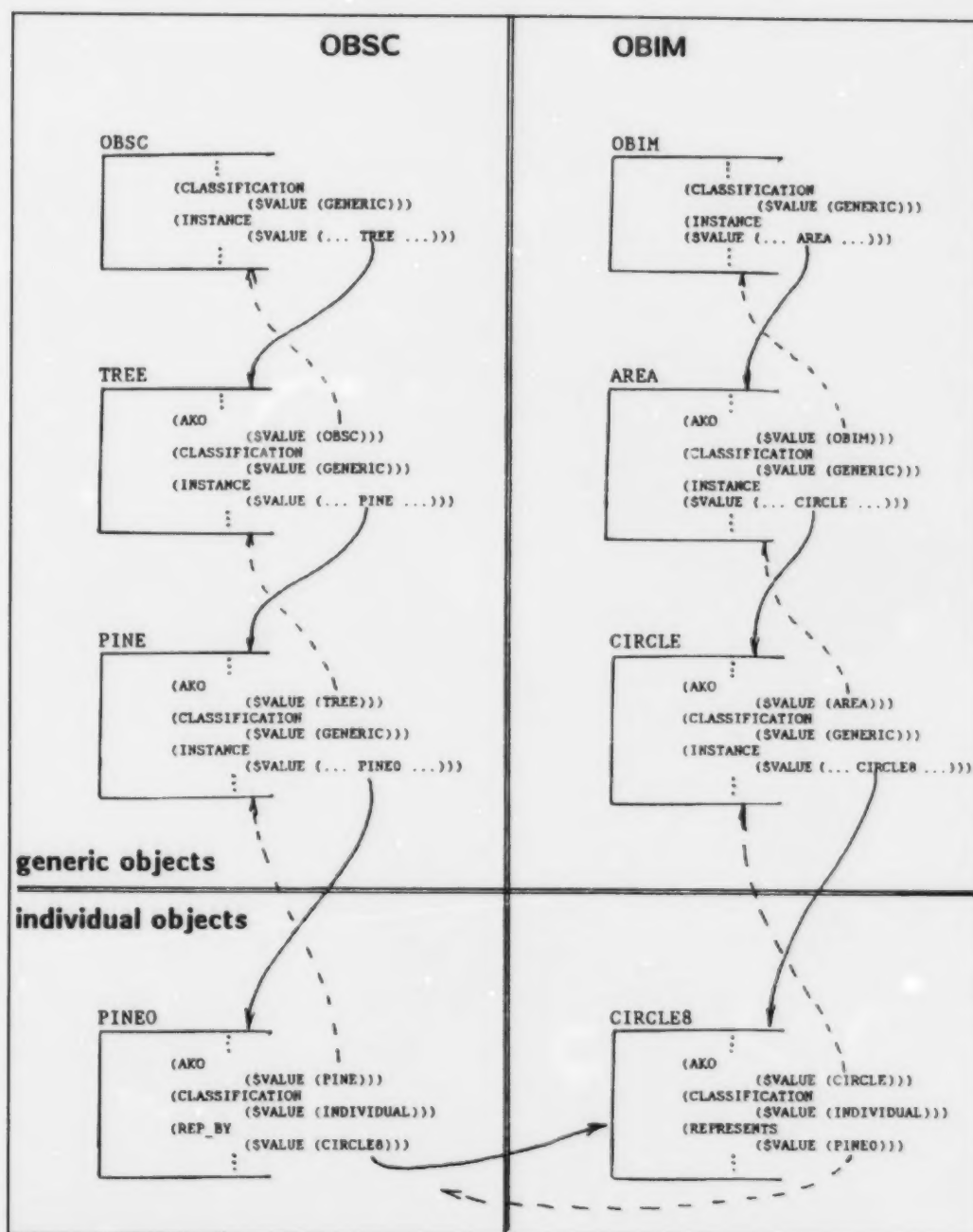


Figure 5. This more detailed example of a representation of scene and image objects shows the hierarchical relationships of generalization/specialization along AKO-INSTANCE relations as well as the REP_BY-REPRESENTS relations between scene and image objects.

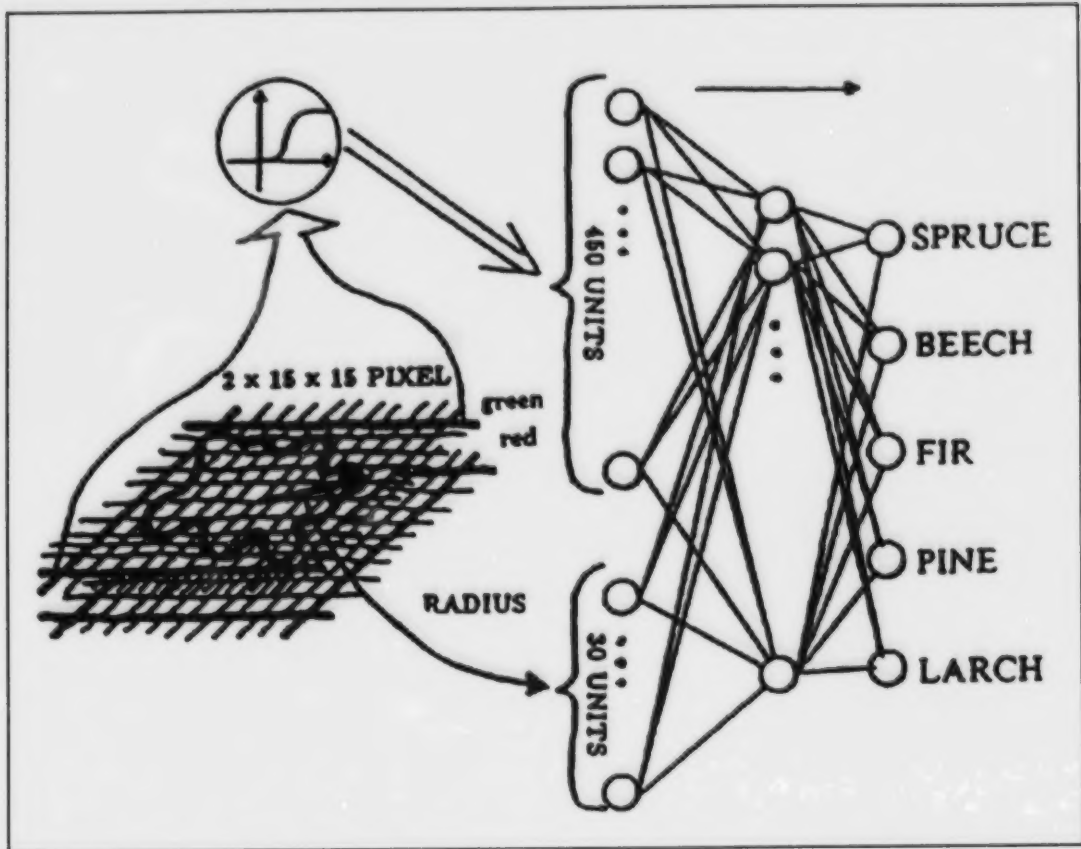


Figure 6. A three layer feed forward neural network architecture for the recognition of five different tree species. The pixel matrix of two spectral layers (red and green) is directly mapped to 450 input units by a sigmoid activation function. Additional 30 input units are used to code the radius estimated by VES.

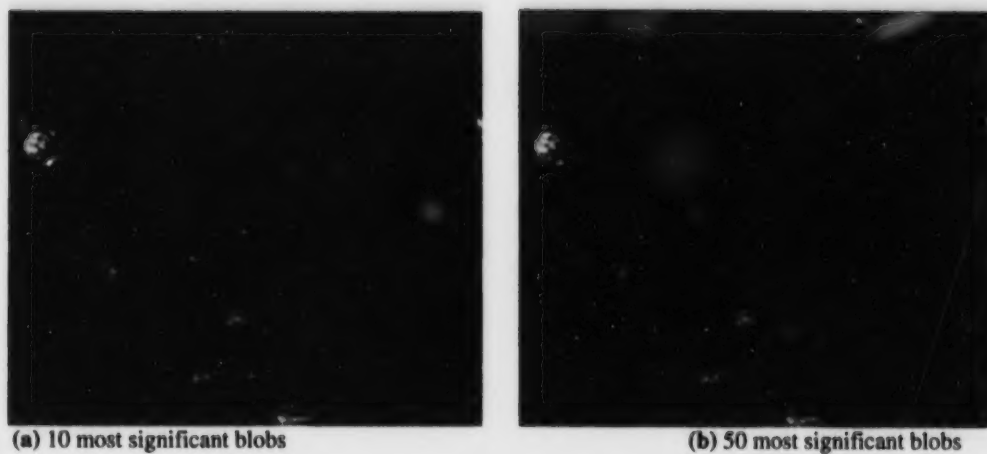


Figure 7. Blob detection with automatic scale selection in 460×402 pixel image using 50 scales r between 1 and 2048.



Figure 8. 1000 blobs detected by automatic scale selection in 2400^2 pixel image using 50 scales r between 1 and 1280.

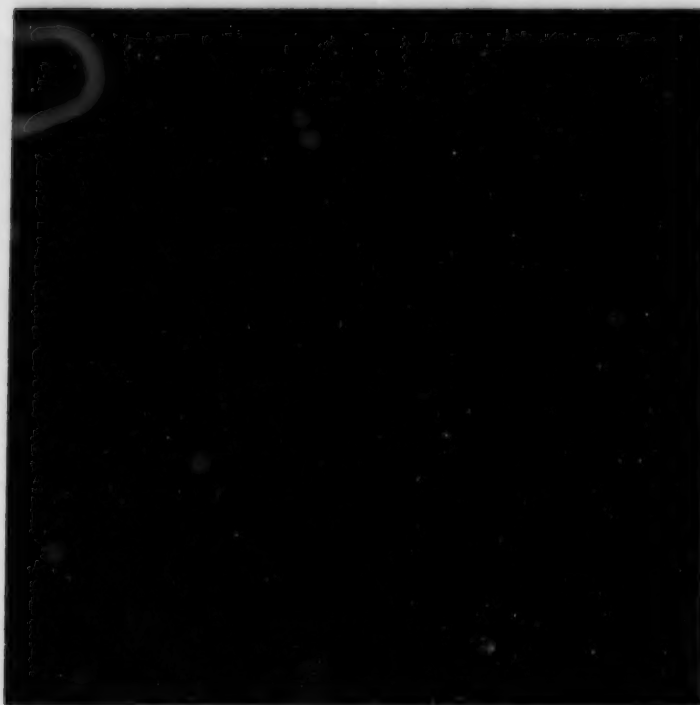


Figure 9. 2500 blobs detected by automatic scale selection in 2400^2 pixel image using 50 scales t between 1 and 1280.



(a) 50 most significant blobs.



(b) 100 most significant blobs.

Figure 10. Blobs detected by automatic scale selection in 501×404 pixel image using 50 scales t between 1 and 512.



(a) 10 most significant blobs.



(b) 25 most significant blobs.

Figure 11. Blob detection by automatic scale selection in a 502 x 404 pixel image using 50 scales t between 1 and 2048.



(a) Blobs for t between 1 and 128.



(b) Blobs for t between 1 and 512.

Figure 12. Both images show the 250 most significant blobs detected by automatic scale selection for two different ranges of t . There is no major difference between the two images, which demonstrates the significance of the extracted blobs.

AN ASSESSMENT OF BOTH VISUAL AND AUTOMATED TREE COUNTING AND SPECIES IDENTIFICATION WITH HIGH SPATIAL RESOLUTION MULTISPECTRAL IMAGERY

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ABSTRACT

Thirty six centimeter MEIS multispectral imagery was acquired over a test site containing boreal and temperate forest softwood and hardwood species in eastern Ontario, Canada. Twenty four 20x20 meter field plots were established identifying the location, species, crown diameters, dominance and openness of each tree within the plot. Trees were manually outlined on the MEIS imagery and used to classify tree species with a maximum likelihood classifier. A visual enhancement was produced to highlight the different species. Trees were automatically isolated using a valley following approach and tree counts and delineations compared to those of the ground truth trees.

Operational photo-interpreters from the provinces of Quebec and Ontario were trained in interpretation of the enhancement and an interpretation test conducted on an individual tree basis. Species interpretation accuracy was in the order of 70-90% for softwood species and down to 50-65% or lower for hardwoods. Accuracy was assessed against the dominance, crown size, crown openness, and species relative to adjacent trees. Preliminary analysis of manually delineated trees produced classifications comparable for some species, but generally in the order of 15% less accurate than the visual interpretation. Visual detection of trees for imagery resampled to different resolutions indicated that optimum detection occurred with resolutions of 10-45 pixels per tree (10 for hardwoods and 25-45 for softwood species). Omission errors dropped rapidly to near 10% at 10-15 pixels/tree then decreased slowly. Commission errors (counting one crown as more than one crown) increased gradually with number of pixels per crown. Accuracies again were assessed against dominance, crown size, crown openness and species. Preliminary tree detection with the valley following approach on the 36 cm data resulted in close estimates of overall average stems/ha, but only 40% direct 1 to 1 correspondence with ground truth trees. The visual counting accuracy was on average approximately 75%.

Keywords: photointerpretation, forest inventory, stems/ha, remote sensing, image analysis, resolution, MEIS.

RÉSUMÉ

ÉVALUATION DU COMPTAGE VISUEL ET AUTOMATISÉ DES ARBRES ET DE L'IDENTIFICATION DES ESPÈCES À L'AIDE DE L'IMAGERIE SPATIALE MULTISPECTRALE À HAUTE RÉOLUTION.

Des images multispectrales MEIS de 36 cm ont été prises au-dessus d'un site d'essai en forêts boréales et tempérées de résineux et de feuillus de l'est de l'Ontario, Canada. On a délimité 24 parcelles de terrain de 20 x 20 m indiquant l'emplacement, l'espèce, le diamètre des houppiers, la dominance et la plénitude de chaque arbre dans chaque parcelle. Les arbres ont été délimités manuellement sur l'imagerie MEIS et on les a utilisés pour classifier les espèces avec un classificateur de probabilité maximale. On a produit une accentuation

visuelle pour mettre en relief les différentes espèces. Les arbres ont été automatiquement isolés à l'aide de la technique de traçage de vallées tandis que les comptes d'arbres et leur délimitation ont été comparés à ceux obtenus en vérité-sol.

Des photo-interpréteurs opérationnels venant des provinces du Québec et de l'Ontario ont été formés pour interpréter les accentuations, et des tests d'interprétation ont été effectués sur une base individuelle, c'est-à-dire arbre par arbre. La précision d'interprétation des espèces était de l'ordre de 70 % à 90 % pour les résineux et de 50 % à 65 % ou moins pour les feuillus. La précision a été évaluée en fonction de la dominance, de la dimension et de la plénitude du houppier, et des espèces parmi les arbres adjacents. Les analyses préliminaires concernant les arbres délimités manuellement ont permis de produire une classification comparable pour certaines espèces, mais généralement dans l'ordre de 15 % ou moins. La détection visuelle des arbres pour de l'imagerie rééchantillonnée à diverses résolutions a permis d'indiquer que la détection était optimale avec des résolutions de 10 à 45 pixels par arbre (10 pour les feuillus et de 25 à 45 pour les résineux). Les erreurs de comptage (comptage d'un houppier comme s'il s'agissait de plus d'un houppier) augmentaient graduellement avec le nombre de pixels par houppier. Les précisions ont encore une fois été évaluées en fonction de la dominance, de la dimension et de la plénitude des houppiers et des espèces. La détection préliminaire d'arbres à l'aide de la technique de traçage de vallées sur les données recueillies à 36 cm a permis d'établir de bonnes estimations de la moyenne globale tige/ha, mais la correspondance 1 à 1 n'a été obtenue que dans 40 % des cas lorsque les données ont été comparées aux données de vérité-sol. Le comptage visuel était, en moyenne, précis à près de 75 %.

INTRODUCTION

High resolution digital multispectral imagery is beginning to be interpreted both visually and with computer-based automated techniques for forest parameters. Key parameters are the detection and counting of individual trees and subsequent interpretation of their species. The capabilities of visual interpretation of such media itself is not well documented. Automated tree isolation and species classification is a new field and studies are needed to define their potential and limitations. This study defines some individual capabilities of visual interpretation and one automated isolation and classification method. The comparison of these capabilities using the same imagery and ground truth provides insight into both avenues of the technology and the possibilities for hybrid methods. The comparison is particularly interesting as it uses high quality imagery and interpreters, and the visual interpretation should represent a good baseline for what is achievable with this type of data. Given the observational and analytical skills of the human interpreter, the visual interpretation results should represent close to a maximum that automated methods can be expected to achieve with the imagery.

SITE AND DATA

SITE

The test site is the Petawawa Research Forest, Ontario, Canada approximately 200 km northwest of the city of Ottawa (46° 00' N, 77° 25' W). It is in the Great Lakes- St. Lawrence forest region in a transition zone between boreal and temperate forests. Boreal and temperate species occur in pure and mixed stands. Common species are: red pine (*Pinus resinosa*), white pine (*Pinus strobus*), jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), eastern white cedar (*Thuja occidentalis*), tamarack (*Larix laricina*), aspen (*Populus*), maple (*Acer*) and white birch (*Betula papyrifera*). Plantations, intensively managed, and natural stands of all ages occur. The test plots for this study are in mature natural stands.

IMAGE DATA AND PREPROCESSING

Thirty six centimeter resolution multispectral imagery was acquired with the MEIS II (Multispectral Electro-optical Imaging Scanner) linear array imager (McColl et al., 1983). Six nadir and a forward and an aft looking channel were recorded in the following wavebands: 449 nm +/- 15 nm; 548 nm +/- 16; 640 +/- 18; 675

+/- 20; 873 +/- 27 and 1018 +/- 55, plus 777 nm +/- 33 nm for the stereo fore and aft channels. Only the nadir bands were used in this study and the 1018 nm band was excluded because of poor quality. There are two flight lines of approximately 6 and 12 km long. Field of view was +/- 20° and swath width 360 m. Data was flown by Innotech Aviation Ltd. on August 16, 1988.

Imagery was radiometrically adjusted to account for the effects of the illumination and view angle (bidirectional reflectance distribution function; BRDF) by an empirical method described by Leckie et al. (1995). The radiance variation across the imagery for softwood stands is modeled and used to correct the radiance of each pixel in each column of the original imagery. The imagery of the two flight lines was then radiometrically normalized by a simple and small additive offset.

In order to test interpretation capabilities at different resolutions, the imagery was resampled to 18 cm, 72 cm and 144 cm with a cubic convolution resampling kernel. It must be remembered that the results from the 18 cm resampled data do not represent the capabilities of data acquired at 18 cm. For convenience, a mosaic of the plots was created in which 200x200 pixel tiles around each plot were pieced together into one test image for each resolution.

Various enhancements using the five nadir bands were tested for their capability for visual interpretation. The enhancement used in this study was custom stretches of the 873 nm, 489 nm and 675 nm band displayed as red, green and blue, respectively. An on-line interpretation key was created for reference during interpretation. Figure 1 gives a subsection of the plot mosaic enhancement with the plot boundaries outlined.

GROUND DATA

Automated and visual interpretation results were tested against ground truth information acquired for 24 ground plots incorporating 600 trees of 17 species. Plots were 20x20 m. Trees were stem mapped, crown shape and size were sketched, and species, diameter breast height, and crown diameter were recorded. The dominance and openness relative to adjacent trees was estimated. Whether the tree was in a pure species setting or there was a species mixture in its surround was also noted. For some tree species underrepresented in the main plots, additional mini-plots were created. Cloney et al. (1993) describes the ground truth data.

Trees were located on the imagery and then their crown was carefully outlined on the image with the computer display system in the lab using all available information.

PROCEDURES

VISUAL INTERPRETATION TEST

The visual interpretation test was conducted on the computer screen with access to an on-line interpretation key giving examples of appearance of different species. Tree counting and species identification were done in a separate procedure. The interpreters were given training on the interpretation of the imagery. They were then presented with the enhancements with the centre of each tree marked and asked to give the species. The interpretation key was arranged so that it was on the same computer screen and could be moved around the screen close to the test tree of interest. Continuous zoom capability was also available. Care was taken to ensure the interpreter did not get fatigued or go awry in the interpretations. Ordering of which of the four resolutions and 24 plots were done first was varied among interpreters to reduce possibilities of bias and tree remembering. All seventeen species were used in the test. The ease of interpretation of each tree was recorded by the interpreter and overall interpretation times documented. Interpreters were thoroughly debriefed. Each interpreter spent a week with the test which was conducted at separate times for each interpreter.

Seven interpreters were tested; five were operational photo-interpreters from Quebec or Ontario. They were therefore familiar with the forest types and species being interpreted. Their experience ranged from 3 to 20 years, with most having over 15 years experience. Two of the interpreters were inexperienced in interpretation.

Tree detection and counting were done in a separate test. The enhancements were presented with the plot outlines overlaid on the screen. The interpreters were asked to identify the presence of any trees within the plot and mark the location of the crown centre. The correspondence of these to the delineated ground truth trees was then assessed. Two types of errors were considered. An omission error occurred when the interpreter failed to locate a tree. Commission errors were when the interpreter counted a tree that was not there, but almost always commission errors were counting a single tree crown as more than one crown. Counting a tree as one extra crown (1:2 correspondence) was most common, but sometimes there was a 1 to 3 correspondence giving two extra crowns, or on rare occasions the crown was portioned into 4 crowns (a 1:4 relationship). Commission error was the number of trees counted as more than one crown converted to a percent of the total number of ground truth trees. Omission is simply the number of trees missed as a percent of total trees. The total error or accuracy is therefore the sum of the omission and commission errors and thus the total number of ground truth trees miscounted. It must be noted that a subset of the plots was tested and, although each interpreter interpreted the same plots at each resolution (except the 144 cm resolution), the plots were not necessarily the same for the different resolutions tested. Only the 5 experienced interpreters conducted the tree count test.

AUTOMATED INTERPRETATION TEST

Automated interpretation was done with the ITC suite of software (Gougeon, 1995, 1998). Figure 2 shows a subsection of the plot mosaic with trees automatically isolated and classified. The automated tree isolation method is based on identifying shadow areas between trees and, starting from minima image intensity values within shadow areas, following valleys in the intensity to produce an initial separation of trees. A rule based system that follows the tree edges is then used in order to outline and further refine the tree isolation (Gougeon, 1995, 1998). The procedures termed ITCVFOL and ITCISOL were applied to the 36 cm data. The infrared band was filtered with a 3x3 window average filter before being used in ITCVFOL. Only the 36 cm data was tested. It should be noted that ITCVFOL and ITCISOL were developed primarily for coniferous stands, and additional methods are still under development. Refinement of procedures specifically for hardwoods and this data set was not done. One limitation in the present implementation is that the minimum size of tree which will be isolated is a 2x2 pixel area. Tree counts were compared with the ground truth delineated trees by several methods: summary of total stems in the plot versus actual number; visual 1 to 1 correspondence of the automatically isolated trees with the manually delineated ground truth trees; and correspondence with delineated ground truth trees based on computer overlay and percentage of area overlap between the isolated and ground trees. The percent overlap in this latter procedure can be set at a user specified threshold.

Single tree classifications were done with a maximum likelihood algorithm incorporated into the ITC software suite. The classification included 13 species (Table 4). For reporting, the results for the red and sugar maple and the trembling and largetooth aspen were combined into one maple and one aspen class. Various band combinations and signature types were tested. Results given are for class signatures generated from a single value for each tree within that class. In this case the value for each tree was what is termed the "average lit" value, which is meant to represent the mean of pixels on the sunlit side of the trees. It is calculated as the average of only those pixels with values greater than the mean value for all the pixels for that tree. The covariance for the maximum likelihood equation is the global covariance matrix for all trees of all species classes combined (not the individual class covariance matrices). The manually delineated trees were used in this analysis. A subset was reserved for training the classification and a second for testing. The classification was then conducted again with the test set used for training and original training set for testing. The accuracies presented are the combination of the results from the two classifications.

TREE COUNT RESULTS

Table 1 gives the visual interpretation tree detection and counting accuracy for the different resolutions. It can be seen that overall accuracy decreases for lower resolutions, although there is not a large difference until between 72 cm and 144 cm resolution. Omission errors clearly increase with lower resolution. Because of the poor counting with the 144 cm data, further analyses of the various influences on visual counting accuracy use results from only the 18 cm, 36 cm and 72 cm resolutions combined, unless otherwise stated. Tree density

(openness relative to adjacent trees) had an important influence on counting accuracy. Accuracy for trees in low, medium and high density settings were 83%, 71% and 72%, respectively. Dominance also had an influence with accuracy being 78% for dominant trees and 72% for codominant. There was no trend in accuracy based on species mixture of surrounding trees.

Resolution (cm)	Total Accuracy	Omission (%)	Commission (%)
18	79	8	13
36	74	13	13
72	72	22	6
144	44	24	32

Table 1. Visual tree count results (% accuracy and error).

For the automated tree isolation, results were good on a plot basis with overall stems/ha for all plots being a 9% overestimate (495 stems/ha versus 455 stems/ha from the ground truth). Indeed crown area as determined from the crowns of manually and automatically delineated trees was an overestimate of only 2%. These averages on a plot basis can be misleading. If one assesses 1:1 correspondence of automatically isolated crowns and manually delineated ground truth trees, there was a 41% correspondence, 42% for softwoods and 37% for hardwoods. As well, examining how 1:1 correspondence changes depending on percent overlap of the automated and manual delineations, exact correspondence was poor as seen below.

<u>Automated 1:1 Correspondence @ n% overlap</u>					
% overlap	50	60	70	80	90
% correspond.	58	44	29	16	4

Species and tree size had a strong influence. The tree species best detected and counted were similar for both visual and automated counting. Table 2 lists the species in order of counting accuracy. It appears that species with peaked, conical well isolated crowns are most easily counted. Black spruce, white spruce and jack pine were best on both visual and automated counts and birch, maple and aspen were poorer. Anomalies between the automated and visual were red pine, which was good on visual but poor on automated classification, and white pine which, although still of intermediate accuracy, was one of the poorer ones for visual interpretation. The cedar for the study had poor counting accuracy, but results may in general be better. Some of the test plots contained cedar which were particularly dense and intertwined with adjacent trees.

<u>VISUAL</u>	<u>AUTOMATED</u>
Black Spruce	White Spruce
White Spruce	Jack Pine
Jack Pine	Black Spruce
Red Pine	White Pine
Maples	White Birch
Larch	Aspens
Aspens	Larch
White Birch	Maples
White Pine	Cedar
Cedar	Red Pine

Table 2. Order of most accurately counted species for both visual interpretation and automated counting.

Tree size was an important parameter for tree counting. The influence of size was only analyzed in detail for the visual interpretation tests, but the general trends in results are expected to be similar for the automated

technique. Tree size can be expressed in terms of diameter breast height, crown diameter, and height. The influence of these was examined, however, number of pixels per crown is taken as a good overall synthesis of tree size and is analyzed in detail. The results from all resolutions 18 cm to 144 cm are combined. Omission and commission errors must be examined individually. Figures 3 through 5 give results. At very small numbers of pixels per tree, omissions can be large, in the 40% to 60% range. However, omissions decrease rapidly to in the order of 10% at approximately 10 to 15 pixels/crown. There is a more or less asymptotic slow decrease in error afterward. Commission errors, on the other hand, increase gradually with greater number of pixels/crown. This commission error is due to the tendency to portion single crowns into several crowns as resolution increases and more detail in the crown is seen. Lead causes of this portioning are clusters of branches appearing as separate entities and more visibility of internal shading. Due to the increasing commission errors with pixels/crown, best overall counting accuracy does not necessarily occur at higher resolutions as expected. Softwood accuracy peaked at 40-50 pixels/tree and 90%, hardwood accuracy peaked at 5-10 pixels/tree and 87%, and black spruce (with small distinct conical crowns) accuracy peaked at 20-30 pixels/crown and 95%.

The black spruce had low maximum commission error at 20%, likely because of the small compact conical crowns. Omission errors were very small after 25 pixels/crown. Hardwoods were more susceptible to portioning (omissions low, commissions high). Portioning was inconsistent (only 25% of portioned trees were consistently portioned by interpreters), whereas omissions were more consistent (of omitted trees, 55% were omitted by most interpreters).

SPECIES INTERPRETATION RESULTS

Overall visual species interpretation accuracies at the different resolutions is given in Table 3 and individual species accuracies for the 36 cm data are presented in Table 4. Results were similar for the 18 cm, 36 cm and 72 cm data, but accuracies decreased substantially for the 144 cm data. Softwood species were generally interpreted to 70% to 90%. Hardwood interpretation was poor if all species were included. Some of the less common species and differentiation of species of the same genera were difficult. Indeed, separation of largetooth aspen and trembling aspen was very poor and results were combined for Table 4. However, if only undifferentiated aspen, maple and white birch are considered, accuracies of hardwoods were approximately 55% to 65% (Table 5). It is also interesting to note that the best species accuracies of the interpreters (i.e., the accuracies of the interpreters with the best accuracy for the different species), generally ranged from 85% to 90% for the softwoods and 65% to 85% for the main hardwood species. This might be viewed as the high end of the accuracies that could be expected.

Resolution (cm)	Softwoods	Hardwoods	Total
18	72	49	66
36	74	50	67
72	70	43	63
144	56	33	50

Table 3. Species interpretation accuracy (%) for different resolution images.

Influences on softwood species visual interpretation of the 36 cm data were examined. Tree openness or density had a strong influence. Accuracies for low, medium and high density trees were 78%, 69% and 65%, respectively. Dominance was also an important factor with 78% accuracy in softwood species interpretation for dominant trees and 66% for codominant. There was a weak trend with species mixture with low mixture generally giving better results. There was no universal trend with tree size as expressed by diameter breast height, crown diameter or height. The situation can be quite complicated. For example, a large jack pine tree begins to resemble a red pine in terms of structure, whereas smaller trees do not.

<u>SPECIES</u>	<u>% Accuracy</u>
Jack pine (<i>Pinus banksiana</i>)	89
Cedar (<i>Thuja occidentalis</i>)	81
Black Spruce (<i>Picea mariana</i>)	83
White Pine (<i>Pinus strobus</i>)	73
Red Pine (<i>Pinus resinosa</i>)	72
White Spruce (<i>Picea glauca</i>)	71
Hemlock (<i>Tsuga canadensis</i>)	60
Larch (<i>Larix laricina</i>)	58
Balsam Fir (<i>Abies balsamea</i>)	38
White Birch (<i>Betula papyrifera</i>)	63
Aspen (<i>Populus</i>)	60
Sugar Maple (<i>Acer saccharum</i>)	52
Ash (<i>Fraxinus</i>)	39
Red Maple (<i>Acer rubrum</i>)	33
Basswood (<i>Tilia americana</i>)	26
Yellow Birch (<i>Betula alleghaniensis</i>)	24

Table 4. Species accuracy with visual interpretation (16 species).

<u>SPECIES</u>	<u>% Accuracy</u>	
	<u>Visual</u>	<u>automated</u>
Jack pine	89	72
Cedar	81	64
Black Spruce	83	69
White Pine	73	35
Red Pine	72	36
White Spruce	71	58
Larch	58	56
<u>Balsam Fir</u>	<u>38</u>	<u>59</u>
Avg. Softwood	71	56
White Birch	63	66
Aspen	60	62
<u>Maple</u>	<u>54</u>	<u>67</u>
<u>Avg. Hardwood</u>	<u>59</u>	<u>65</u>

Table 5. Species interpretation accuracy with both visual and automated procedures (11 species or species groups).

Table 5 contrasts the species discrimination accuracies for the visual and automated techniques. Accuracies of the automated classification for most softwood species is in the order of 15% less than the visual interpretation. Red and white pine were particularly poorly classified with the automated procedure. Balsam fir, which was badly misinterpreted visually, was much better classified automatically. Accuracies for the hardwoods were similar or slightly better with the automated classification. Tables 6 and 7 give the confusion matrices for the interpretations. There was a fairly even spread of confusion in the visual interpretation. There was high confusion between balsam fir and white spruce and between maple and birch. Considerable amounts (14%) of the aspen trees were interpreted as maple. For the automated interpretation red and jack pine are confused with each other. Jack pine was also somewhat of a 'catch all' class, with at least some trees of most of the other species being classified as jack pine. Somewhat surprisingly, some red pine (15%) and white pine (18%) trees were erroneously classified as aspen. As well, a small percentage of aspen trees were misclassified as each of the other species, even the softwood species.

Interp\Ground	Pj	Pr	Pw	Sw	Sb	Lt	Ce	Fb	A	B	M
Jack Pine	89.4	9.2	0	1.3	0	0	.4	0	2.6	0	.3
Red Pine	8.4	72.6	14.4	2.7	0	0	0	0	8.0	1.3	1.9
White Pine	0	5.1	73.1	2.4	.3	1.4	1.4	5.3	1.9	1.9	0
White Spruce	0	.4	1.8	71.2	2.0	2.7	2.0	22.6	1.6	0	0
Black Spruce	.3	0	0	.3	83.3	26.0	1.6	3.5	0	1.6	0
Larch	0	0	.5	1.1	10.1	57.8	.8	3.9	0	.7	0
Cedar	0	.9	0	2.4	2.2	7.1	80.9	9.7	1.6	2.8	.7
Balsam Fir	0	1.3	1.8	10.0	2.1	2.7	2.2	37.2	.6	.9	0
Aspen	0	2.3	1.8	3.0	0	.3	1.2	3.0	60.5	2.8	.8
Birch	.8	4.8	3.0	1.3	0	1.4	2.2	6.6	6.4	58.3	32.5
Maple	.8	2.5	1.8	.8	0	.3	2.6	1.2	13.7	20.3	53.6
Other (He, Bas, Ash)	.3	.9	1.8	2.5	0	.3	4.7	7.0	3.1	9.4	10.2

Table 6. Confusion matrix of visual interpretation results.

Interp\Ground	Pj	Pr	Pw	Sw	Sb	Lt	Ce	Fb	A	B	M
Jack Pine	72	38	4	8	8	3	11	0	3	9	3
Red Pine	16	36	9	4	2	3	3	4	9	0	3
White Pine	0	0	35	14	2	11	0	5	4	0	3
White Spruce	0	7	13	58	3	0	2	14	4	0	0
Black Spruce	5	0	0	0	69	14	4	0	2	0	0
Larch	0	0	4	2	11	56	3	9	0	0	0
Cedar	2	0	0	2	4	0	64	0	7	0	0
Balsam Fir	5	2	13	12	1	8	9	59	4	0	9
Aspen	0	15	18	0	0	0	2	4	62	12	9
Birch	0	0	0	0	0	0	0	0	3	66	6
Maple	0	0	4	0	0	3	0	5	2	13	67
Unclassified	0	2	0	0	0	2	2	0	0	0	0

Table 7. Confusion matrix of automated classification results.

DISCUSSION OF ACCURACY ASSESSMENT ISSUES

Comparison of visual and automated interpretations based on single tree analysis raises several important issues as to procedures and standards for accuracy assessment. For instance, when is a count correct? One to one correspondence of counted and ground truth trees is a logical method. The question then becomes, when is it 1:1: a given closeness to tree centre, a threshold of percent overlap of outlined area, or an objective human interpretation? How does one account for a one to many count, for example one crown being portioned into four. Is it one, three or four errors? A second viable accuracy assessment procedure is to conduct an area based analysis. Are the stems/ha the same as the ground truth stems/ha? In this case 1:1 correspondence can be poor but the stems/ha quite accurate. Area based assessments can be on strict plot comparison or on a stand basis where the plot values are used to represent expected stand averages. Representativeness is of course an issue in the latter case, but precision as to what trees are in a plot or out is needed in the strict plot comparison method. For instance, the stem of a tree may be outside the plot and not counted, whereas the crown may very well be even fully within the plot. For tree counting with aerial imagery, the tree dominance is a key factor. What dominance level should be included in the ground truth count for comparison with imagery counts? It is not reasonable or perhaps fair to expect imagery counts to be able to account for understory or even most suppressed trees. The goal and use of the counts is an issue here. The concept of counting or at least knowing the number of 'photo visible' trees (trees expected to be visible from above) is useful. A hierarchy of dominance

related to tree size, height and visibility from above is useful to record in the field. Clumping of stems is another problem. Several stems may form a single crown that has no possibility of being distinguished from above. Clumping should also be documented in the field.

Similar issues arise for species composition assessment. Comparison can be done tree for tree. Alternately, plot and area based procedures can be used with percent species composition being represented by numbers (percent) of trees of each species or percent of total crown area of each species. Field plot designs have to reflect the choice of accuracy assessment. Photo visible crowns, crown area or percentage of each species, understory trees and clumping are issues. Assessing species accuracy is not independent of counting or tree detection and delineation accuracy. Accuracy assessment of species composition becomes even more thorny when one considers omission and commission delineation errors (especially portioning of crowns or combining several crowns into one).

This study has taken reasonable approaches to these issues, but also has benefited from a very detailed ground truth set designed for this purpose. Detailed ground truth of this nature, however, is very time consuming and expensive to obtain. Accepted procedures, common terminology and standards need to be developed.

CONCLUSIONS

A robust test of on-screen visual interpretation capability of high resolution multispectral imagery was conducted. It provides a good baseline target or benchmark for which automated techniques using high resolution multispectral imagery can be compared. Visual species interpretation accuracies were generally 70-90% for softwoods; 15% less for the automated classification. Red and white pine were poor for automated interpretation, however, balsam fir was assessed better with the automated classification. Hardwood species were difficult to interpret visually at 55-65% visually. Results were similar or slightly better for automated interpretation. It is important to note that automated classification was better for hardwoods and some of the species more difficult to interpret visually. Visual interpretation accuracy did not vary greatly between the 18 cm, 36 cm and 72 cm data but dropped off rapidly for the 144 cm imagery. Tree density and dominance were important influences on species interpretation, accuracies being lower for higher density and for codominant trees.

Density (tree openness) and dominance were also important for tree counting. Species was important as well. Peaked or conical compact softwood species such as black and white spruce were most accurately counted with both visual and automated techniques. Failings were similar, for instance, hardwoods and big trees suffer from portioning. Accuracies for the visual tree counting were in the order of 70 to 80%. Although total stems/ha count among all plots were close with the automated method, one to one correspondence was poor. Visual interpretation results indicate that for tree detection and counting there is an optimum resolution; higher resolution is not necessarily better. The number of pixels per crown yielding the best accuracy varied among species.

Both visual and automated interpretation of high resolution imagery for speciation and tree counting is a new field. There are many different possible enhancements of the imagery and refinements that could be made to the automated methods used. Several important issues related to how to determine accuracy in tree counting, species composition and field data acquisition procedures and design need to be further discussed. Considering the early stage in development of the field of automated interpretation, results compared to those of experienced interpreters using the same data are encouraging.

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and supervised the interpretation tests and analyzed much of the results. Ian Scott (formerly of the Pacific Forestry Centre) did much of the image analysis for the automated interpretation part of the study. The authors also wish to thank the Ministère des Ressources Naturelles du Québec (Service des Inventaires Forestières) and Ontario Ministry of Natural Resources (OMNR) for providing air photo interpreters for the study. The interpreters must be recognized for their hard work and dedication during the week long interpretation test. Interpreters were: Martin Hamel and Réjean Chiasson (Roche Ltd.), Roland Bilodeau (Ministère des Ressources Naturelles de Québec), Eric Wilson and John Cibulski of the OMNR, and Steve Fox and Tom Spooner of Algonquin College, Pembroke.

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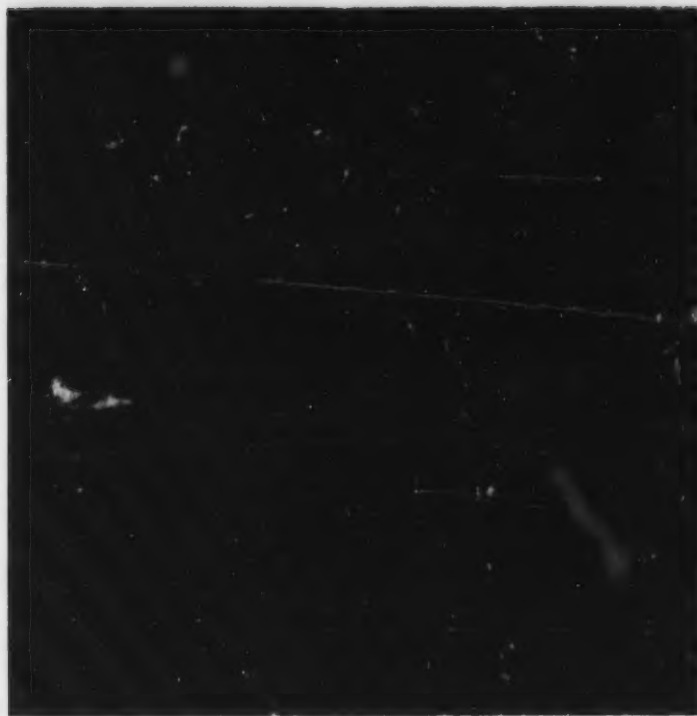


Figure 1. Subsection of the plot mosaic showing the enhancement used in the visual interpretation test and plot boundaries. Resolution is 36 cm.

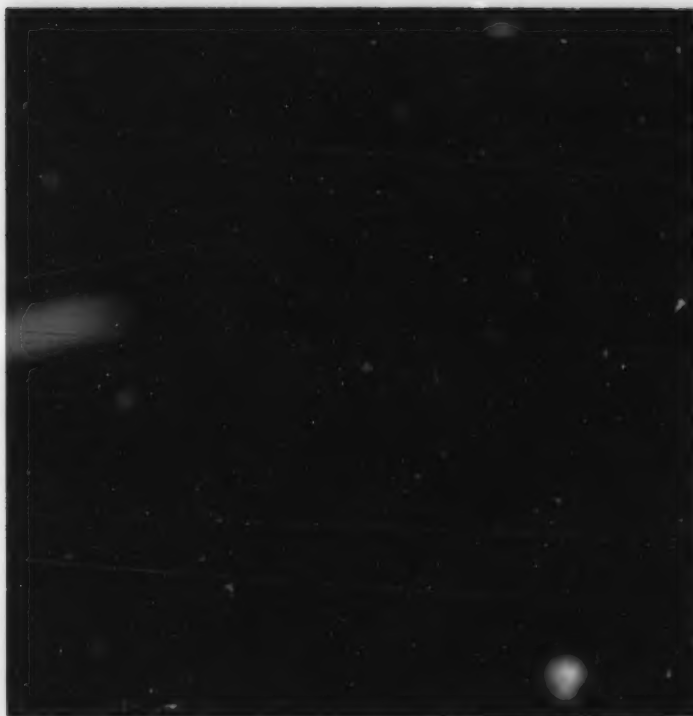


Figure 2. Automatically delineated trees within a subsection of the plot mosaic. Also included is the classification of the delineated trees using signs from manually delineated trees. It must be noted that manually generated trees were used to assess the accuracy of the automated classification, not these delineations.

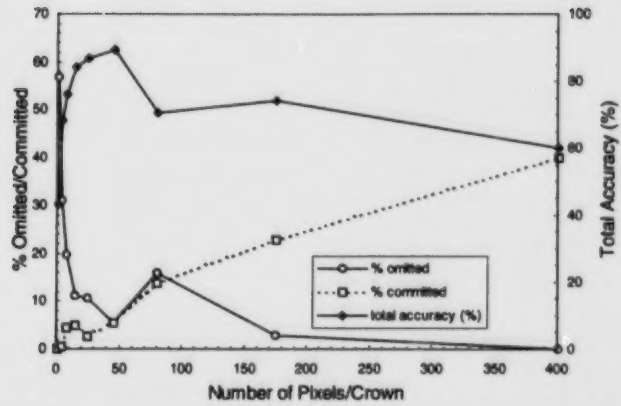


Figure 3. Visual tree counting omission and commission error and total accuracy versus number of pixels per crown for softwoods.

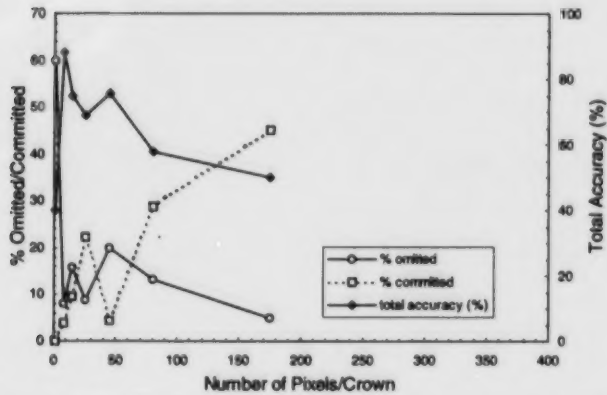


Figure 4. Visual tree counting omission and commission error and total accuracy versus number of pixels per crown for hardwoods.

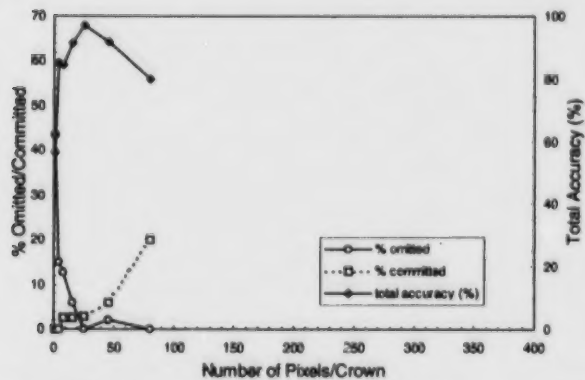


Figure 5. Visual tree counting omission and commission error and total accuracy versus number of pixels per crown for black spruce.

Regeneration and Forest Health

APPLICATION OF CASI¹ REMOTE SENSING TO CLASSIFICATION OF BACKLOG NOT SATISFACTORILY RESTOCKED FOREST IN NORTHERN BRITISH COLUMBIA

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ABSTRACT

A pilot program to detect coniferous stocking and assess classification of backlog not satisfactorily restocked (NSR) areas from areas of satisfactory stocking (SR) was flown with the CASI sensor in April, 1996, in the Dawson Creek, Fort St. John and Fort Nelson areas of northern British Columbia. Areas were flown before leaf-out of the deciduous tree species and brush.

Preliminary results showed promise of the CASI as a useful tool for separating NSR from SR areas. Seedlings were detected at 80 centimetres and smaller, where there were no overhead obstructions. As the density of the overstorey increased, trees had to be larger to be detected.

A further semi-operational trial was initiated in the fall of 1996, after leaf-off. This trial confirmed earlier results that the CASI could be used operationally for classifying NSR/SR areas. Operational flying of backlog NSR areas commenced in the fall of 1997.

While the CASI will give an indication of stocking, there will be areas where not all of the trees will be detected. However, it is anticipated that costs of surveys can be substantially reduced using remote sensing technology, in combination with minor ground-truthing by experienced personnel.

Keyword: CASI, stocking, classification, forestry, remote sensing.

RÉSUMÉ

TÉLÉDÉTECTION À L'AIDE DU CASI¹ POUR CLASSIFIER L'ARRIÉRÉ DES TERRAINS FORESTIERS INSUFFISAMMENT RÉGÉNÉRÉS DANS LE NORD DE LA COLOMBIE-BRITANNIQUE

Programme pilote de détection de l'état de régénération des conifères et d'évaluation de la classification des zones d'arriérés insuffisamment régénérées par rapport aux zones suffisamment régénérées. Le programme a été appliqué au moyen du capteur CASI en avril 1996 dans les secteurs de Dawson Creek, de Fort St. John et de Fort Nelson dans le nord de la Colombie-Britannique. Les secteurs ont été survolés avant la chute des feuilles des espèces à feuilles caduques et des broussailles.

¹ Compact Airborne Spectrographic Imager developed by ITRES Research Limited of Calgary, Alberta.

Les résultats préliminaires montrent que le CASI constitue un outil pratique pour distinguer les zones suffisamment régénérées des zones insuffisamment régénérées. Des arbres de semis de 80 cm et moins ont été détectés dans les endroits non obstrués. Dans les endroits où l'étage dominant était plus important, les arbres devaient être plus gros pour être détectés.

Un autre essai semi-opérationnel a été effectué à l'automne de 1996, après la chute des feuilles. Il a permis de confirmer les résultats antérieurs, démontrant que le CASI pouvait être utilisé de façon opérationnelle pour classer les zones suffisamment régénérées et les zones insuffisamment régénérées. Les vols opérationnels au-dessus des zones d'arrière insuffisamment régénérées ont commencé à l'automne de 1997.

Même si le CASI donne des indications des proportions de surface occupée, il restera des zones qui échapperont à la détection totale des arbres. Cependant, nous prévoyons que les coûts des levés peuvent être substantiellement réduits en utilisant la télédétection en combinaison avec des travaux mineurs de vérité-sol effectués par du personnel expérimenté.

INTRODUCTION

British Columbia, with a land area of approximately 95 million hectares, is the third largest province in Canada. About 85% of British Columbia is designated as "Provincial Forest" which is owned by the province and is managed for all resource values, not just timber. Forestry is extremely important to the BC economy. However, during the decades of the 50's, 60's and 70's insufficient seedlings were being produced to reforest all of the areas that required planting after harvest, with the result that by 1984 about 738 000 hectares harvested prior to 1982 were identified as being "backlog" not satisfactorily restocked. This area has now been substantially reduced through a Federal-Provincial Forest Resource Development Agreement which set a reduction of the backlog NSR as one of its primary goals. By February, 1997, approximately 156 989 hectares of gross pre-82 backlog remained of which 93 818 hectares are considered treatable. In addition, areas harvested between 1982 and October 1, 1987, add a further 119 710 hectares of gross backlog NSR of which 78 636 hectares are considered treatable. The date of denudation is important relative to the classification standards applied.

This paper briefly discusses the results of the use of the CASI sensor for classification of backlog NSR areas in northern British Columbia.

Data was collected in eight spectral bands from 400nm (blue) to 950nm (near infra-red). The CASI was mounted on a twin-engine aircraft and flown at a height of 400 metres, utilising a 300 metre swath width and 40% overlap and providing a 60 centimetre pixel size. The imagery was radiometrically and geometrically (roll, pitch and yaw) corrected. Full georeferencing of the image was made available on standard TRIM maps used by the Ministry of Forests.

The paper also discusses the potential for the use of remote sensing for other applications in forest management.

BACKLOG CLASSIFICATION

As noted previously, backlog NSR is defined in British Columbia as areas denuded prior to October 1, 1987 that are not satisfactorily restocked within acceptable time periods and that are accessible and economically viable to treat. Backlog NSR is divided into two time periods, each with different minimum stocking standards that may be applied, at the discretion of the District Manager. Sites denuded prior to 1982 may have a minimum stocking standard of 400 well-spaced² stems per hectare, while those denuded after 1982

² Well-spaced is based on using a 2 metre intertree distance as the default standard. By definition a well-spaced tree must be free from insect and disease damage, but this was not included in the CASI assessment.

will have a minimum standard applied in accordance with the Establishment to Free Growing Guidebook for the particular ecosystem and site series. In the northern units surveyed this minimum stocking standard is usually 700 well spaced stems per hectare.

Most of the areas in the north have lodgepole pine (*Pinus contorta*) and spruce (*Picea spp.*) often under a canopy of deciduous species, usually aspen (*Populus tremuloides*), birch (*Betula papyrifera*) and willow (*Salix spp.*). While deciduous species are considered as acceptable stocking on some ecosystem associations, the objective of the study was to detect coniferous stocking; therefore, data collection was made during leaf-off.

RESULTS

CASI imagery was first collected in April, 1996, before the deciduous trees had leafed-out. The purpose was to determine the limits for conifer detection, so areas were flown that were stocked as well as over forest management trial areas where exact numbers of planted trees were known. These preliminary results showed that seedlings could be detected down to 50 centimetres, where no overhead obstructions from deciduous species occurred. As the density of the overstorey increased, trees had to be larger to be detected.

Figure 1 shows a false colour image for a Fort Nelson block with two strata identified based on the deciduous overstorey. Figure 2 shows the well-spaced stem map based on using a 2 metre algorithm. Forest health indicators were not included in the assessment of well-spaced. Figure 3 shows the well-spaced stems colour themed for the different densities of stocking. Figure 4 is an example of landcover classification produced from the CASI image.

Further trials were done in the fall of 1996 and in spring 1997. CASI derived tree numbers were compared with numbers obtained from standard ground surveys in July, 1997 (Comparison of CASI with silviculture survey results shown in Table 1.

Block Name /Line	Stratum	Ground Survey (stems/ha)	CASI Derived (stems/ha) ³	Number of Plots	Tree Height (cm)	Deciduous (stem/ha)	Decision
fn3a-2a	A	400±302	309	5	95	200	NSR
fn3a-2b	A	800±330	533	5	134	0	More plots reqd.
fn3b-6	A	633±283	633	6	182	301	NSR
fn3b-6	B	933±170	900	6	308	444	SR
fn3b-8	A	1133±225	891	6	250	133	SR
fn6-15	A	600±381	295	5	184	800	NSR
fn6-15	B	200±?	20	4	50	2500	NSR

Table 1. Comparison of CASI with silviculture survey results.

Note: The CASI-derived stems per hectare are based on the average stems per hectare for the entire stratum.

The ground survey sampled a representative portion of the stratum with 50m² plots at 20m intervals.

Only the minimum number of plots necessary to obtain a reliable sample were installed.

Note that as the deciduous cover gets denser, the numbers of conifers detected decreases. With 2500 stems per hectare of deciduous, and conifers at an average height of 50 centimetres, the CASI sensor had a poor detection success. The important consideration, however, is that in almost all cases the NSR/SR decision, based on a minimum standard of 700 well-spaced stems per hectare, is the same with both the CASI and ground based surveys. In one case (fn3a-2b) more ground plots are required because the standard error reduces the mean below 700.

³ Note that CASI does not have confidence limits as the number is based on the actual trees detected.

OPERATIONAL CONSIDERATIONS

The provincial grand total of pre-October 1, 1987 backlog, all of which should be surveyed to assess the treatable area, is 276 699 hectares. Current costs for ground based surveys range from \$30 to \$50 per hectare and often more in remote areas where the only access is by helicopter or boat. Fixed wing data acquisition by CASI, with a 60 cm pixel size, ranges from \$10 to \$12 per hectare. This includes data acquisition, processing, summary statistics, with hard copy and electronic map outputs to update forest cover maps.

At a 60 cm pixel size the CASI will not detect all trees in a cutblock, but the forester then has the ability to concentrate his efforts on areas where no trees were detected and to conduct additional assessments. Trees will not be detected where: the size is generally less than 60 to 80 centimetres with no overstorey; there is a deciduous overstorey sufficiently dense to block coniferous trees from the sensor; or, there are no trees on site. In any of these cases a decision has to be made whether stocking is, or is not, acceptable, or whether a treatment has to be carried out.

At this time the CASI is not able to differentiate coniferous tree species at the regeneration size. Therefore, after an area has been declared stocked with a sufficient number of well-spaced stems, it will be necessary for someone with experience to do a cursory examination of the site to determine the species mixture and to complete an inventory label. This step, however, will be considerably less than the normal time spent on ground surveys.

The CASI will be particularly advantageous on older remote areas where there is very poor or no access. On those sites trees are often already larger than 80 centimetres and detection will be much improved.

FUTURE APPLICATIONS

In 1997, further trials with the CASI sensor, mounted on a helicopter and utilising a 40 centimetres pixel size, were conducted. At time of press results are not yet available, but it is hoped that smaller trees will be detected and that differentiation between species can be made. One of the advantages of using a helicopter is that specific blocks, and blocks of small size, can be more easily targeted than by using a fixed-wing aircraft which requires long flight lines to be cost effective.

Future potential uses of the CASI, or other remote sensing techniques, are to audit current blocks for free-growing assessments where trees are required to have a minimum height (usually 1 metre for spruce and 2 meters for pine) or to determine gaps in plantations that may need to be brought to full stocking. Further, CASI will likely show a real advantage in assessing areas for "green-up" where trees are required to be 3 meters in height and species differentiation is not particularly important. Because of the ability to determine areas of bare mineral soil, CASI could be used to make site disturbance assessments or to determine the percentage of the area in roads and landings.

Other potential uses include: forest inventory; making broad assessments of forest health to identify harvesting opportunities; finding suitable areas for juvenile spacing or commercial thinning; and to assist with block layout, in particular with reference to delineating riparian areas.

CONCLUSION

With current techniques and the considerably higher resolution now available with remote sensing tools, the opportunities for application to forest management can now be fully realised.

ACKNOWLEDGEMENTS

Funding for this project was provided by Forest Renewal BC with additional technical contributions from ITRES Research Limited.

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Figure 1. False colour CASI imagery of a Fort Nelson block classified as NSR.

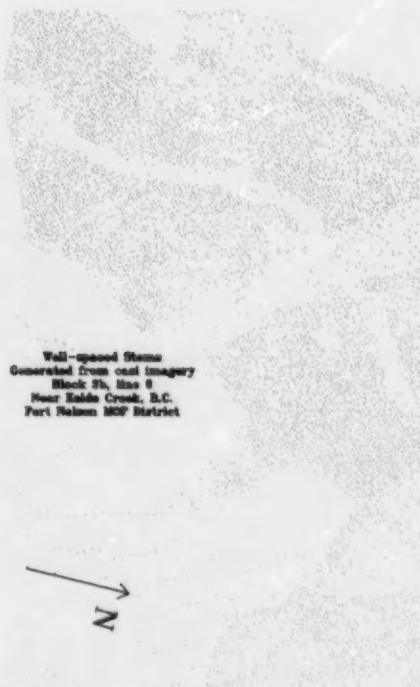


Figure 2. Well-spaced map after applying a 2-metre algorithm.

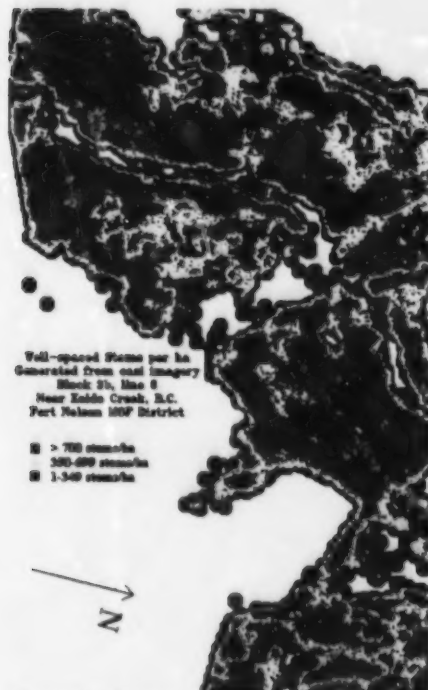


Figure 3. Well-spaced stems colour themed for the different densities of stocking.



Figure 4. Landcover Classification for the Fort Nelson block.

OPERATIONAL TECHNIQUES FOR ASSESSING NSR AREAS USING AN AIRBORNE MULTISPECTRAL IMAGER (CASI)

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ABSTRACT

Airborne multi-spectral (CASI) imagery has been acquired for approximately 80,000 hectares in the Prince George Forestry Region in B.C. This work has included validation test area at the Inga Lake Experimental Test Site and a more operational test at Big Lake in the Dawson Creek District. The validation work showed that the CASI can reliably detect individual isolated conifers down to about 75 cm height provided there are no significant obscuring effects due to deciduous trees or shrubs. The conifers are detected using spectral signatures. Then a "well-spaced" mask is applied to remove stems that are too close to other stems. The forest cover polygons are imported digitally and stem densities are calculated for each polygon and output as attribute file for each polygon. The stem densities are also calculated locally using a circular kernel of 0.1 ha size. The resultant stem density maps show the high variability of stem densities within most forest cover polygons. Finally, an example of an OAF (Operational Adjustment Factor) calculation is shown. The OAF image is generated by superimposing a disk of 2.7m diameter on each identified well-spaced stem and then calculating the residual gaps.

RÉSUMÉ

TECHNIQUES OPÉRATIONNELLES D'ÉVALUATION DE ZONES FORESTIÈRES INSUFFISAMMENT RÉGÉNÉRÉES À L'AIDE D'UN SPECTROMÈTRE IMAGEUR AÉROPORTÉ (CASI)

L'imagerie du spectromètre aéroporté (CASI) a été recueillie dans une zone couvrant environ 80 000 ha dans la région forestière de Prince George, en Colombie-Britannique. Les travaux comprenaient les zones d'essai de validation sur le site d'essai expérimental du lac Inga et un essai plus opérationnel au lac Big dans le district de Dawson Creek. Les travaux de validation ont permis d'indiquer que le CASI peut détecter avec fiabilité des conifères isolés d'une hauteur d'environ 75 cm, dans la mesure où aucun effet obscurcissant important n'est causé par des arbres à feuilles caduques ou des broussailles. Les conifères sont détectés d'après leur signature spectrale. Ensuite, un masque "bien dégagé" est appliqué pour enlever les tiges qui sont trop rapprochées les unes des autres. Les polygones du couvert forestier sont importés sous forme numérique et la densité des tiges est calculée pour chaque polygone, et sortie sous forme de fichiers d'attribut pour chaque polygone. La densité des tiges est aussi calculée localement à l'aide d'un cercle de 0,1 ha. Les cartes résultantes montrent une haute variabilité de densité de tiges dans la plupart des polygones de couvert forestier. Enfin, on montre un exemple de calcul de sortie sous forme de fichiers d'attribut de type 1. Ce type de calcul est généré en surimposant un disque de 2,7 m de diamètre sur chaque tige identifiée et bien dégagée et en calculant ensuite les espaces résiduels.

INTRODUCTION

This program was initiated to introduce CASI imagery into the assessment of NSR (Not Satisfactorily Restocked) blocks in northern B.C.. The technical challenge was to detect and produce stem maps of small conifer trees in large remote regions that would be expensive to ground survey. The presence of a deciduous overstorey obscuring the conifer trees required that the imagery be acquired during leaf-off in the spring or fall. Since the CASI imagery is georeferenced the stem counts can be linked to forestry databases using existing vector polygons. Once it was determined that conifer stems could be detected, large operational programs (approximately 20,000 ha per season) were established and other output products could be produced (e.g. OAF gap assessments).

TEST PROGRAM

The objectives of the initial NSR programs were to test the ability of CASI imagery to stem map individual regeneration conifer trees and to establish the detection limits of the trees in terms of height, deciduous overstorey, and surrounding background landcover types. CASI imagery with 60 cm resolution and eight spectral bands was collected over a diverse set of regions in the Dawson Creek district in the spring of 1996 during leaf-off.

Many of the sites were visited shortly after the flights by ITRES and MOF personnel with hardcopy false colour imagery for an initial evaluation of the detectability of the conifers. These initial field visits indicated that the detection limit of individual conifer stems could be detected to about 75 cm where there was no deciduous overstorey. Trees of about 1 m could be detected through light deciduous overstorey. For the sites where conifer trees could not be detected because of a very dense deciduous overstorey it was determined the sites would require brushing of the deciduous overstorey. The conifer detection was not dependent upon the background landcover type except when the conifers were surrounded by grass that had turned green, in which case single pixel conifer trees could not be identified.

The CASI imagery was then analyzed for detection of individual conifer stems and compared with detailed ground truth data at the Inga Lake Research Site. Figure 1a shows a roll corrected flight line of the western half of the Inga Lake site and 1b shows the conifer stem map and the outline of the plot boundaries. At Inga Lake over 4,000 trees have detailed ground information; however, a detailed tree-by-tree comparison was only conducted for a handful of the test plots. Although an exhaustive comparison was not conducted, the results from Inga Lake confirmed the initial inspection results of a detection limit of about 75 cm height in open areas and slightly higher than 1 m in areas of deciduous overstorey.

The spring 1996 CASI imagery was also used for an operational test. A mosaicked CASI image was generated for nine flight lines in the Big Lake area of the Dawson Creek district. After the stem positions were estimated from the imagery, a filtering process is applied to eliminate the stems that are too close together (figure 2). The "well-spaced" criteria for this area is 2m inter-tree spacing. The well-spaced stem map was smoothed to create the well-spaced stems per ha image in figure 3. The output image colours indicate the stocking levels with red being > 700 stems per ha and thereby can be labeled as satisfactorily restocked (SR). One quarter of this approximately 100 ha region was surveyed with standard 50 m² plots for every ha. Within the white polygon in figure 3, CASI measured 493 stems per ha compared with 568±100 for the ground surveys. The CASI image provides foresters with a comprehensive view of the stocking within the block and indicates the regions of the polygon that require fill planting. The fraction of this block that is satisfactorily restocked is 15%.

OPERATIONAL PROGRAMS

The utilization of CASI imagery in assessing NSR blocks has been extended to operational programs in the Fort Nelson, Fort St. John and Dawson Creek districts. CASI imagery has been acquired at a rate of about 20,000 ha per leaf-off season in fall 1996, spring 1997, and fall 1998. The validation of this program is summarized by Browne and Fletcher (these proceedings).

The CASI imagery is orthorectified into mosaics and analyzed according to the NSR polygons provided by the forest cover polygons. Figure 4a shows a polygon of a sample NSR block near Tumbler Ridge B.C. overlaid onto a true colour image. Only the imagery within the polygon is analyzed as shown in the stem map in Figure 4b. The resulting stem counts are delivered to the foresters in a table (see Table 1) that references the forest cover polygons. Along with the statistical summary for each polygon map, products are also generated based on the 1:10,000 B.C.G.S. mapping system. The information map products also include an overlay of the NSR polygons and TRIM planimetry.

Forest Cover Block name	816
Forest Cover Map Number	93P016
Stand Area (hectares)	2.43
Number of Trees Detected	923
Number of Well-spaced Trees	668
Total Stem Density (stems/hectare)	379
Well-spaced Stem Density (stems/hectare)	274

Table 1. Regeneration stem counts based on forest cover polygon

ESTIMATION OF OAFS

The identification of stem positions of regeneration conifers has been extended to estimate future gaps in the mature forest. A pilot project was undertaken to compare the OAF gap estimates calculated from CASI imagery with ground survey methods and high-resolution aerial photography. The aerial photography and ground survey methods were carried out by Laing and McCullough of Smithers B.C. The project site was along the Bowron River south-east of Prince George, B.C. The CASI imagery was acquired in fall 1996 with 60 cm pixel resolution.

A false colour CASI image of the site is shown in Figure 5a, and the gap image is shown in Figure 5b. This image simulates the future crown coverage of the stand and therefore indicates gaps in the stocking.

Table 2 shows the results of the stocking gaps estimates by the three different methods for four plots. The CASI and ortho-photo techniques are in better agreement with each other than they are with the ground survey results. This is likely because the tree distribution in the plots is quite patchy and therefore not well sampled by the ground data.

Site No.	Ground (point)	Ground (line)	Ortho-photo	CASI
1	4.6	3.7	5.5	3.0
2a	0	0.6	1.2	5.0
2b	21.2	18.5	31.3	36.0
2c	6.7	2.6	8.9	13.0
2 (Average)	9.9	7.3	13.1	15.7

Table 2. OAF gap assessment comparison

SUMMARY

This paper summarizes the evolution in the utilization of CASI imagery in assessing stocking of NSR blocks from the initial test plots to operational programs and includes the extension to other products such as OAF gap analysis.

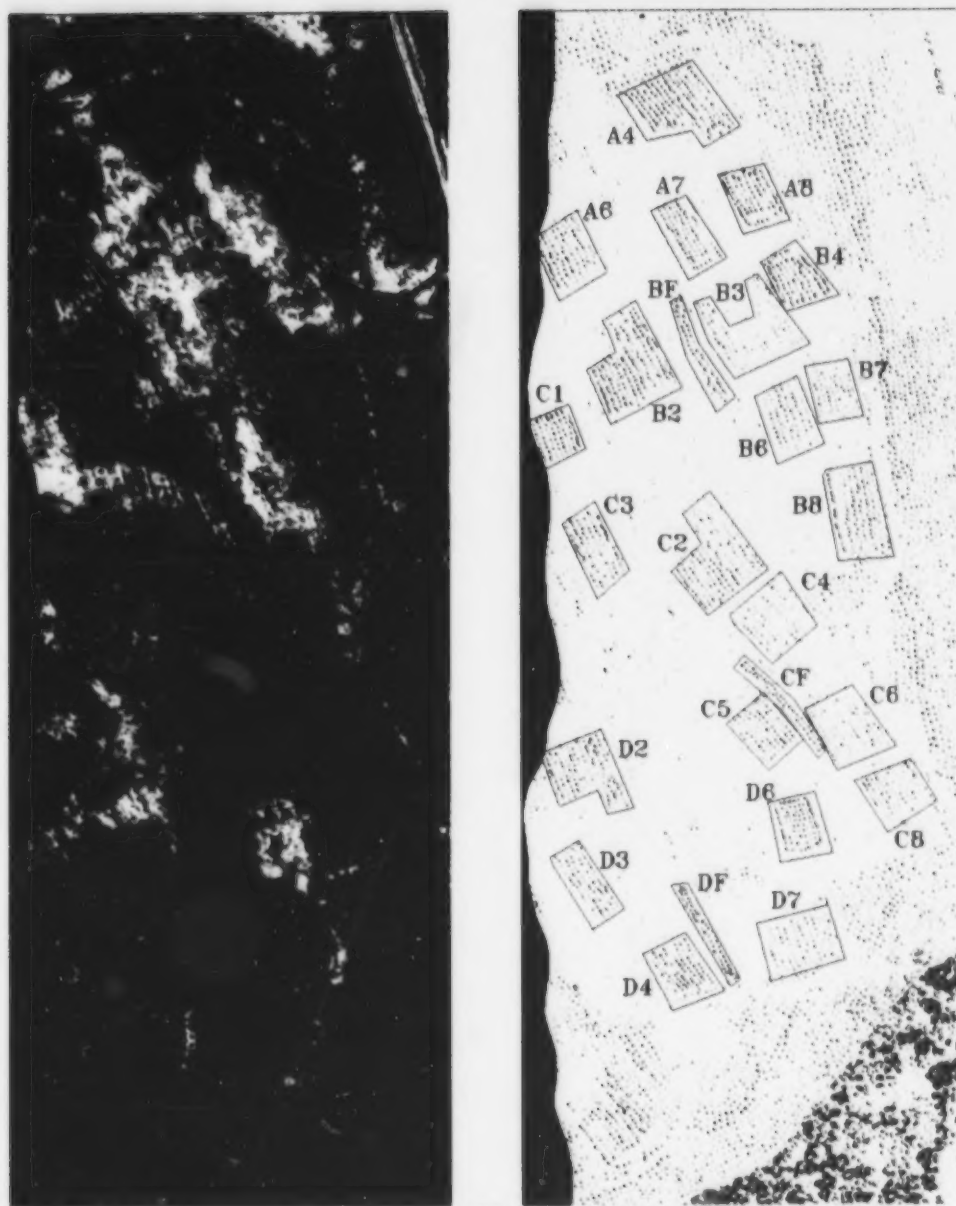


Figure 1. False colour image and conifer bitmap of the east side of Inga Lake FRDA test site. The bitmap outlines and labels the blocks according to the FRDA site schematic. The small conifers designated in the bitmap are not readily apparent in the raw CASI image.

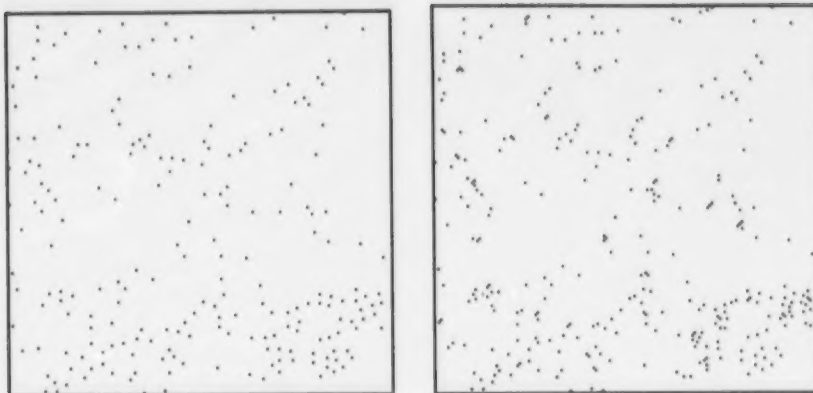


Figure 2. Illustration of filtering method for well-spacing conifer stems on a 1 ha block. The left image is for total stems and contains 317 stems. The right image is after well-spacing with a 2m spacing criteria.



Figure 3. Well-spaced stems per ha image for the operational test block near Big Lake in the Dawson Creek District. The red portions of the image comprise 15% of the image and are classified as SR (satisfactorily restocked) since they have >700 well-spaced stems per ha. Within the white polygon the CASI method produced 493 stems per ha while ground surveys found 568 $\pm$ 94 stems per ha.

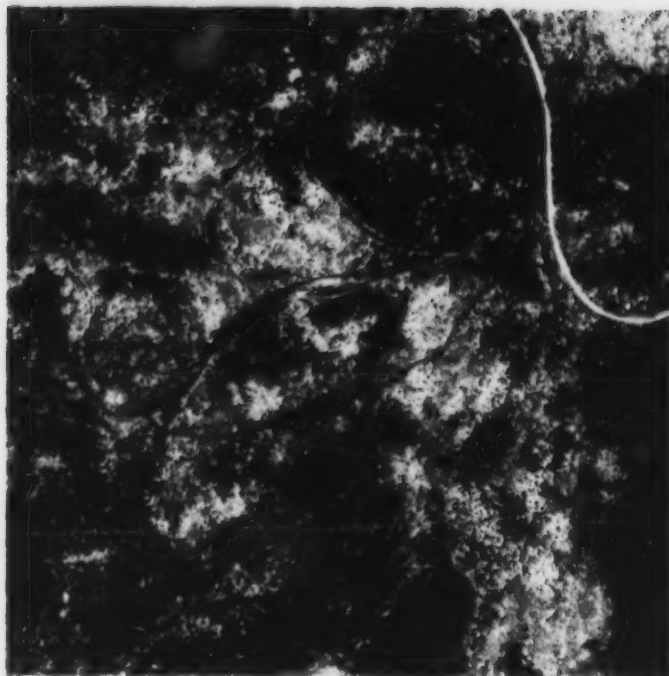


Figure 4a. True colour CASI image with forest cover vector of NSR stand 816.



Figure 4b. Analysis is performed according to forest cover polygon. The stem positions of small conifers are analyzed only within the NSR stand 816.

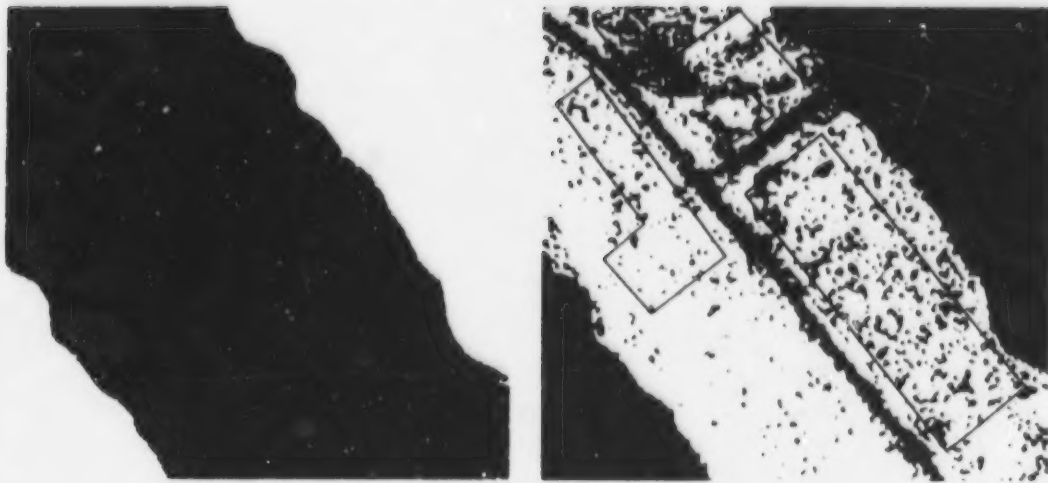


Figure 5a. is the false colour CASI image of the Bowron River OAF site and the 5b is the resultant OAF image. The OAF image is created by locating the individual stem positions and convolving them with a 5.4 metre disk to simulate the size of a mature conifer. The resulting holes in the imagery represent gaps in the canopy once the forest reaches maturity.

FOREST REGENERATION: INDIVIDUAL TREE CROWN DETECTION TECHNIQUES FOR DENSITY AND STOCKING ASSESSMENTS

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ABSTRACT

Sustainable forest management depends on successful forest regeneration. The use of remotely sensed aerial images or digitized aerial photographs of high spatial resolution could lead to accurate and timely semi-automatic computerized assessments. Techniques based on individual tree crown detection or delineation can produce information about regenerating areas such as stem density, proper tree spacing and stocking, and even possibly, tree species and health estimations.

Various computerized tree crown detection and delineation techniques already exist. Some are geared towards dense stands, while others are aimed at open areas. An hybrid detection technique is able to detect the situation at hand and switch paradigm accordingly. Delineation techniques require higher spatial resolution and/or tree sizes, but offer more promises for tree species recognition and health estimation. Most techniques can benefit from particular acquisition conditions (e.g., autumn acquisition) and simple pre-processing techniques to increase their detection or delineation capability and accuracy.

This article describes two techniques presently under investigation by the authors: one of crown detection only, and another capable of crown delineation. Their strengths and weaknesses are illustrated and discussed, as are their pre-processing needs and image acquisition criteria. Various pre-processing techniques are explored. Preliminary results with aerial images of regeneration stands of various ages and densities demonstrate more quantitatively these strengths and weaknesses relative to measurements made on the ground and from aerial photographs.

RÉSUMÉ

RÉGÉNÉRATION DES FORÊTS : TECHNIQUES DE DÉTECTION DES HOUPPIERS EN VUE D'ÉVALUER LA DENSITÉ DES PEUPELEMENTS ET LES SURFACES OCCUPÉES

L'aménagement forestier durable repose sur une régénération fructueuse. L'utilisation d'images aériennes télédéteçtées ou de photographies aériennes numérisées à haute résolution spatiale pourrait mener à la réalisation d'évaluations informatisées et semi-automatiques précises et opportunes. Les techniques basées sur la détection ou la délimitation des houppiers peuvent permettre d'obtenir des informations sur les zones de régénération (densité des tiges, espacement entre les arbres, peuplement, voire même espèces d'arbres et estimations sur leur état de santé).

Il existe déjà diverses techniques informatisées de détection et de délimitation des houppiers. Certaines s'appliquent plus facilement dans les peuplements denses tandis que d'autres sont mieux adaptées aux zones

dégagées. Une technique hybride de détection pourrait s'adapter aux conditions en présence et commuter les paradigmes en conséquence. Les techniques de délimitation nécessitent des résolutions spatiales plus élevées et/ou des arbres plus gros, mais elles sont plus prometteuses en ce qui à trait à la reconnaissance des espèces d'arbres et à l'estimation de leur état de santé. La plupart des techniques peuvent tirer avantage de conditions d'acquisition particulières (en automne, par exemple) et de techniques simples de prétraitement pour améliorer la capacité et la précision de délimitation et de détection.

Cet article présente la description de deux techniques en cours d'étude par les auteurs; la première porte sur la détection des houppiers seulement et l'autre sur la délimitation des houppiers. On y discute des points forts et des points faibles de chacune, avec illustrations à l'appui, ainsi que des exigences relatives au prétraitement et des critères d'acquisition d'images. On y examine également diverses techniques de prétraitement. Les résultats préliminaires des analyses d'images aériennes de peuplements en régénération à divers âges et de diverses densités démontrent ces forces et ces faiblesses d'une manière plus quantitative par rapport aux mesures effectuées au sol et aux photographies aériennes.

INTRODUCTION

Forest regeneration, whether natural or the result of planting, is essential to sustainable forest management. Individual foresters are made increasingly responsible, before cuts are even allowed, for prescribing a course of action after logging, monitoring the results, and taking corrective actions when needed. Consequently, they require accurate, timely, and preferably inexpensive information about the vegetation development in recently cut (or burned) areas. Wagner (1994) describes forest vegetation management as "that part of silviculture directed at manipulating the rate and course of early plant succession to achieve a forest stand of a particular composition, structure, and form, within a specified period of time". Practicing good forest vegetation management is vital to Canada's competitiveness and is increasingly important to forest companies as only areas demonstrated sufficiently restocked to count towards allowable cut quotas.

Generally, several vegetation surveys are conducted during the early development of a forest stand to assess its progress, decide if corrective actions are needed, or determine if the prescription's goals were reached. Not all surveys are exhaustive, but in any given survey, information may be gathered on density, stocking, distribution, survival, health, species composition, brush competition and regeneration performance. These parameters lead to decisions as to whether an area is judged "under or overstocked", whether brush competition is considered "acceptable" or "unacceptable", whether the regenerating species is determined "free to grow", or whether corrective measures should be applied. Density, "a measure of the number of trees per unit area", and stocking, "the number of well-spaced trees relative to some reference density" (Brand, 1988), are two of the most important parameters and are often costly to acquire. Only density, spacing and crown diameters are addressed in the preliminary work reported here.

Although at this point in time forest managers are still evaluating regeneration success/failure using simple overflight estimations by inspectors, assessments from aerial photograph and/or field measurements as needed, "research is needed in preparation for the imminent digital era" (Pitt *et al.*, 1996). Even if the images from the new generation of high resolution (0.8-5 m/pixel) satellites (Fritz, 1996) are unlikely to be very useful in regeneration assessments, the existence of various digital airborne sensors and the possible digitization of aerial photographs make digital approaches conceivable. Today's stricter requirements make increasingly mandatory the exact quantification of regeneration, rendering ubiquitous the more costly assessments by field sampling. Cost savings and potential gains in efficiency could be achieved if certifiable, preferably automatic, techniques were to be developed based on computer image analysis. This paper presents a snap-shot in time of an ongoing research effort. It describes two techniques presently under investigations: one of crown detection only, capable of stocking and density assessments; and another, of crown delineation, capable of stocking and density assessments with larger trees (or higher resolution images), as well as, crown area assessments and possibly, species recognition and health assessments. Each technique's strengths and weaknesses, as well as, pre-processing and image acquisition requirements, are illustrated and discussed briefly.

TECHNIQUES AND METHODS

In previous work (Gougeon, 1997), a locally adaptive (or hybrid) technique for forest regeneration assessments was developed. It is based on the improvement of a technique originally developed to detect mature trees and identify their species in medium resolution images (1-3 m/pixel) (Gougeon & Moore, 1989), a technique which has been used extensively by others since then (Eldridge, 1993; McLaughlin *et al.*, 1996; Dralle & Rudemo, 1996). The technique consists in detecting, with or without a priori smoothing, local maxima in the most appropriate spectral band (typically the near-infrared). In dense coniferous stands, where individual tree crowns appear separated by areas of shade, the algorithm generally isolates a single pixel per tree, usually corresponding to its well illuminated tree top. However, in sparser stands where sun illuminated ground is also visible, the algorithm picks up numerous false positives on the ground. To remedy this situation, a new version of the algorithm was created that looks for a specific shadow (i.e., an area of shade at a specific distance and direction based on sun angle) for each potential tree top. Later, the two versions of the algorithm were combined into a locally adaptive algorithm that switches between the two modes based on an a priori obtained mask derived from a directionality index based on an accumulation of local gradient directions. This locally adaptive (or hybrid) technique permits the detection of young and older trees, in dense as well as open stands, with few false positives.

Although this new hybrid technique is appropriate for stem density, spacing regularity, and stocking assessments, there is a need to assess older regenerating areas for growth and health. These two factors are better assessed if full crown measurements are available. A system of individual tree crown (ITC) delineation and classification developed to improve the precision and timeliness of forest inventories of mature trees seen at around 30-100 cm/pixel (Gougeon, 1995; 1998) could work well with sizeable regeneration in higher resolution images (10-30 cm). Unfortunately, the existing ITC-based system has problems similar to the original local maxima approach mentioned above. It relies on valleys of shade between tree crowns to separate them from each other and from the background material. It thus works well on moderate to dense coniferous stands, but has not yet been adapted to work with more open stands where bright backgrounds are visible. A simple adaptation scheme is used here. It is based on the idea that if the bright background material can successfully be classified as a distinct feature, it can be removed from the image before the ITC delineation software is run. The generic case may imply the creation of a "rough" classification with an unsupervised pixel-based classifier and the use of certain classes as masks in the ITC-based system. However, here, because of the autumn image acquisition and the senescence of the competing vegetation, a simpler and more automatic approach can be used. It consist in creating the required mask using a simple rule applied to the multispectral image: "retain only areas that have higher normalized near-infrared radiances than their average normalized radiance in the visible bands", where the normalization process consists in dividing any radiance by the average radiance of its channel. This essentially gets rid of the well illuminated background of senescent material without affecting the tree crown themselves, because of their strong near-infrared returns.

After the individual trees are detected, information such as stem counts or density (per ha.), average tree spacing, and percentage of area properly stocked (properly spaced) can be easily obtained for any given forest stand. With the latter technique, crown areas, and possibly species and health information are also available. Since the prescribed stocking is usually known, areas of under and over stocking can be automatically highlighted. If for some reason the prescribed stocking is unknown to the image analyst, areas that diverge from what should be expected given the average tree density can be highlighted. Similarly, if stands are not known a priori, it is possible to get reasonable automatic stand boundaries based on factors such as stem densities (Gougeon *et al.*, 1998). The stand polygons and the information about their content could then be transferred to a forest inventory residing on a geographic information system.

IMAGE AND GROUND DATA

This ongoing research work towards the production of automatic forest regeneration assessments was carried out on a MEIS-II (McColl *et al.*, 1983) image of the Sturgeon area, Petawawa Research Forest, Ontario (approximately 46° of latitude and 78° of longitude). A partial, yet detailed, ground survey of the area was also available. The image was acquired in November 1982, at a spatial resolution of 30 cm/pixel (Figure 1). It contains (Figure 2) plantations of jack pines (*Pinus banksiana*) and Scots pines (*Pinus sylvestris*) of different

ages (3-10 years old) and spacings (1.5 - 4 m). In the denser and older stands, the individual tree crowns are completely surrounded by shade. In the more open or younger stands, the ground is clearly visible. It is covered by grasses, sedges and herbaceous plants. For the more open older stands, individual tree shadows are also visible when trees are sufficiently high.

This simple situation, with coniferous trees of uniform size and spacing, and low lying ground vegetation that has senesced, turned brown or lost its leaves, is ideal for initial algorithms development. The main complications from an image analysis point of view are the low sun elevation and the dune-like rolls of the terrain which make the ground of open stands visibly bright in some areas and dark in others. These bright areas present high radiances in all of the spectral bands making difficult the isolation of the young conifers. However, in general, the autumn acquisition should facilitate the separation of the coniferous material from other ground vegetation.

RESULTS AND DISCUSSION

Both techniques were applied to the near-infrared channel of the 30 cm/pixel MEIS image of the Sturgeon Plantation (Figure 1). The mask used with the locally adaptive technique to automatically switch between the shade-based approach and the shadow-based approach is shown in Figure 3. It is based on a directionality index calculated from an accumulation of local gradient directions from the original image. More specifically, an intermediate image was produced where areas that have more directionality in a direction commensurate with that of the sun's illumination are given higher values and a threshold was used to produce the mask itself. It seems to correspond well with the areas where visible tree shadows are present. Occasionally, areas of dense regeneration, where directional shadows are not expected, are also covered by the mask. However, this does not create a problem since both the shade-based and the shadow-based approaches tend to perform well on these areas. The mask also covers an area where scarification lines are visible (upper left corner) and happen to be in the same direction as the typical shadows. Although a potential problem, if considered purely from the point of view of pin-pointing areas containing tree shadows, in this particular case the results from this anomaly are actually beneficial. Indeed, the effect of the mask is to summon the shadow-based approach because it has stricter decision criteria than the shade-based approach, and diminishes the quantity of false positives that an area like this one typically produces.

The results of the locally adaptive technique are shown in Figure 4. A first visual assessment of the trees that were pin-pointed by the locally adaptive approach reveals that it offers great potential for the automatic assessment of regeneration. Most of the young trees present in the image are rather well accounted for. A few false positives are encountered on occasion, mainly in the more open stands, essentially, where the directionality mask failed. Of course, areas devoid of trees also generated considerable false positives. However, it is often possible to mask out these areas a priori with a little preprocessing, as done for the second technique (below), or based on auxiliary information, as was done here by manually creating a mask for the roads. The locally adaptive technique permits a reasonable assessment of all the stands, whether very young, or more mature, in dense or open arrangements, as shown in Table 1.

Figure 5 shows a first attempt (Gougeon, 1996) at tree crown delineation in regenerating areas using the ITC-suite. As expected, it performs well in dense stands where the brighter trees, separated by darker valleys of shade, are easily delineated. However, it fails miserably in open areas where trees are hard to separate from the bright background material. In these areas, the crowns are delineated as very large patches that typically include as much background material as crown material. Numerous patches of purely background material are also delineated, making tree counts, as well as, tree crown area estimations, erroneous. Figure 5 illustrates well the necessity of getting rid of the brightly illuminated background material before the ITC-based techniques can be useful with more open stands.

Figure 6 shows the results obtained with the ITC delineation software after brightly illuminated background areas were removed from the input image by the rule-based pre-processing. It led to better crown delineation and counts in the open areas, while still producing good and sometimes better results in dense stands. However, crown areas may be underestimated in some cases and overestimated in others. The underestimation is most obvious when realizing that the vast majority of the younger trees (<5 years old) are

missing (compared with Figure 5). They do not meet the minimum requirement of the ITC-suite for 2x2 pixel of crown material before attempting to delineate a tree crown. This can probably be attributed to the preprocessing rule having a tendency to eliminate pixels that are not of pure crown material and thus, eliminate a lot of the mixels that could otherwise be considered part of the crowns. On the other hand, since the rule is less likely to be triggered in areas with darker background material, the crown areas there may be slightly overestimated because mixels are more readily considered part of the crowns. Finally, another interesting aspect of this approach is that the rule-based preprocessing seems to eliminate almost all false positives in areas devoid of trees.

Table 1 shows some of the regeneration assessment measurements taken on the ground and the corresponding assessments resulting from the first technique (hybrid tree top) and the second technique (masked-ITC). For the latter, areas 2 and 4 were not considered because of the technique's obvious failure at delineating tree crowns there (as explained above). The agreement is generally very good. The two automatic methods seem to agree well ($\pm 12\%$) with each other on stem counts, density and spacing. The two methods also agree well ($\pm 15\%$) with the ground measurements for stem density, spacing, and crown diameters, except for the stem densities of regions 1 and 3. However, the stand areas here are so small (0.3-0.5 ha) that minor imprecisions in delineating the stand boundaries or minor differences in stem counts can change the stem densities significantly. Finally, because the software is still under development and several stock estimating criteria are under consideration, stocking assessments were not reported.

ON-GOING WORK

These encouraging results need to be verified more thoroughly and for repeatability. The area under scrutiny and several other areas have been the subject of a comparison between ground counts and photointerpretation counts done on aerial photographs and on MEIS-II images at different spatial resolutions (Brand *et al.*, 1991). A quantitative comparison with these new techniques is in the works and as are stocking assessments. Also, since one of the available MEIS-II images was acquired in August (vs. November here), it may be possible to assess the significance of image acquisition in late autumn, specially relative to the preprocessing rule used in the second technique. In addition, that rule could possibly be applied to the first technique to help in the automatic elimination of non-forested areas. It also needs to be tested for consistency in other situations and with other sensors. Later, with other datasets, species differentiations and tree health assessments should be explored.

CONCLUSION

Regeneration assessments are a crucial part of managing forests for sustainability. Potential gains in efficiency could be made if reliable assessments can be obtained from the automatic analysis of digital images. This work represents first attempts at detecting individual trees in order to automatically evaluate regeneration density, spacing, stocking, and average tree crown areas. The two techniques presented here permit the detection of young and older trees, in dense as well as open stands, with few false positives. These apparent successes need to be quantified better and checked for repeatability. This is the subject of ongoing work.

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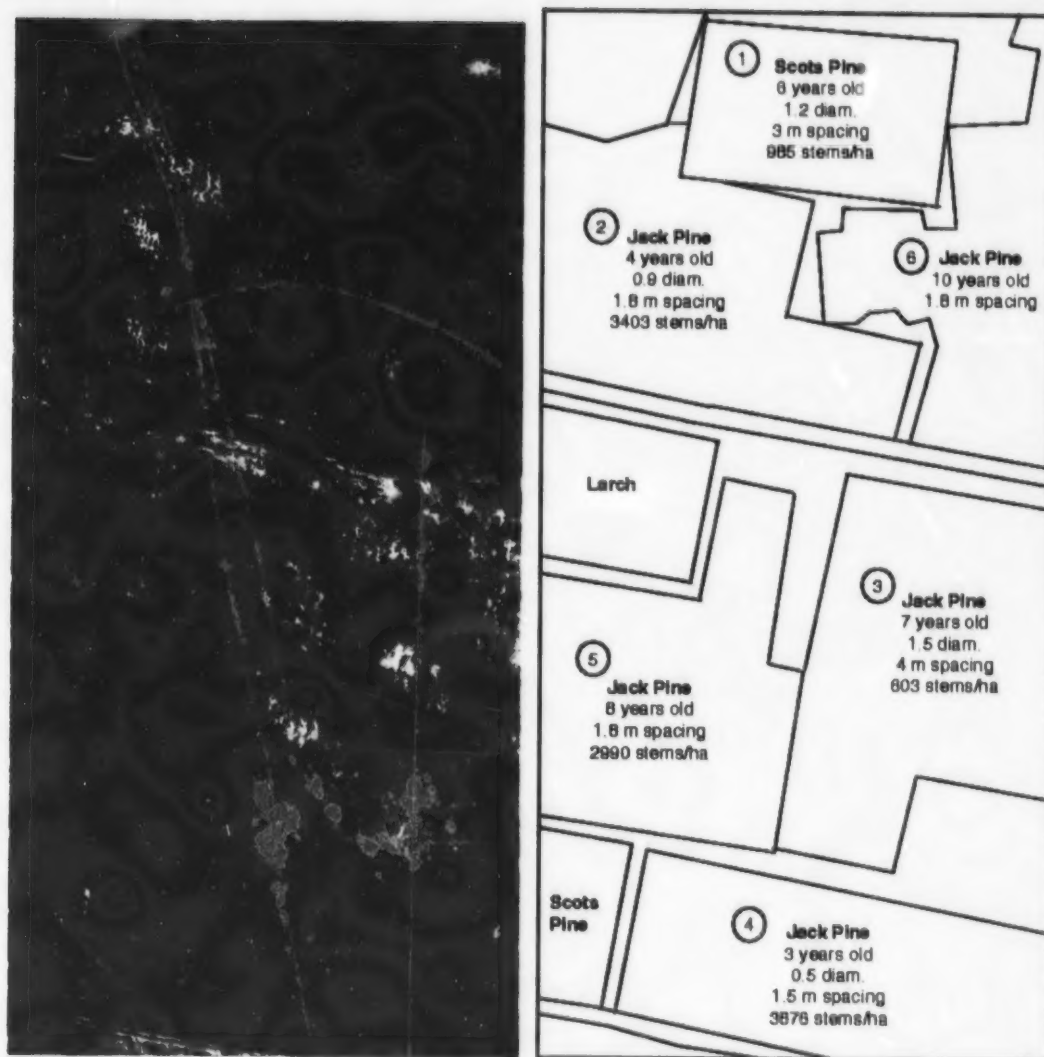


Figure 1 (left). Pseudo-colour infrared view of a MEIS-II image (30 cm/pixel) of the Sturgeon Plantation in the Petawawa Research Forest near Chalk River, Ontario (from Gougeon, 1997).

Figure 2 (right). Characteristics of the regeneration stands in Figure 1 (after Gougeon, 1997).



Figure 3 (left). Image of high directionality in directions commensurate with the sun angle (Gougeon, 1997).

Figure 4 (right). Results from the hybrid locally adaptive approach which can deal with most open and dense stands. In open stands, a shadow in a specific direction (commensurate with that of the sun's direction) has to be detected before the local maxima is considered to represent a tree. Non-forested areas could have been masked out (Gougeon, 1997).

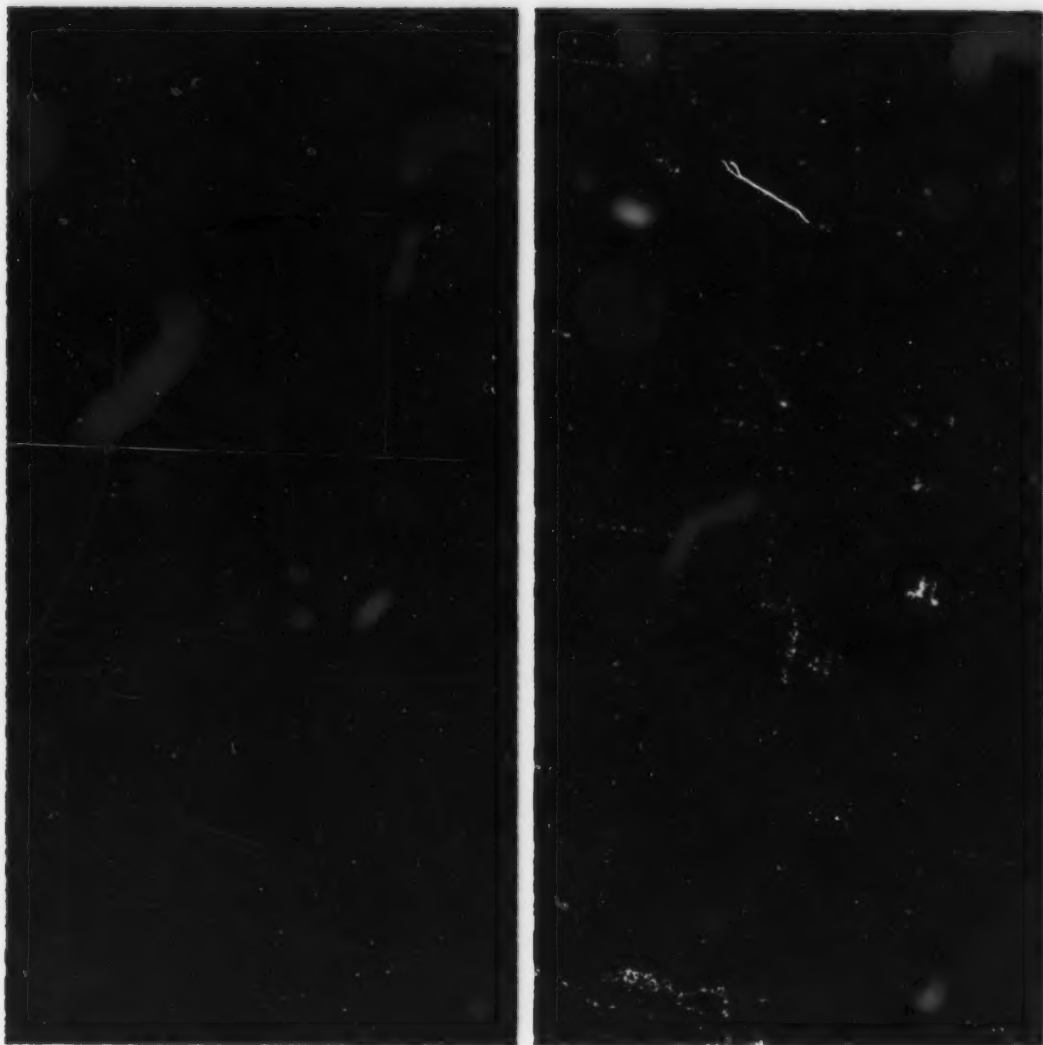


Figure 5 (left). Previous attempt at tree crown delineation using the ITC-suite without any pre-processing to eliminate the bright background of competing, but senescing vegetation (Gougeon, 1996).

Figure 6 (right). Delineation of tree crowns with the ITC-suite after bright background areas were removed from consideration using a simple multispectral rule. Provides crown areas and more potential for species identification and health analysis.

Table 1 - Regeneration Assessments												
Ground assessment						First technique (hybrid TT)			Second technique (masked-ITC)			
Site	Species	Age	Diam.	Spacing	Density	Stems	Density	Spacing	Stems	Density	Spacing	Diam.
1	Ps	6	1.2	3.0	985	517	1407	2.7	463	1259	2.82	1.28
2	Pj	4	0.9	1.8	3403	1219	3247	1.75				
3	Pj	7	1.5	4.0	803	554	864	3.4	553	862	3.4	1.36
4	Pj	3	0.5	1.5	3876	317	4333	1.52				
5	Pj	8	—	1.8	2990	1611	3020	1.82	1796	3367	1.72	1.27
6	Pj	10	—	1.8	—	936	2477	2.01	998	2641	1.95	1.29



DETECTION AND CLASSIFICATION OF FOREST DAMAGE CAUSED BY TOMENTOSUS ROOT ROT USING AN AIRBORNE MULTISPECTRAL IMAGER (CASI)

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ABSTRACT

This study represents a preliminary test of 0.6 meter multispectral imagery for detection of symptoms of tomentosus root rot at the individual tree level and at the stand level at a location in central British Columbia using the Compact Airborne Spectrographic Imager (CASI). This test utilized an automated isolation of individual conifer tree crowns followed by a tree by tree health classification. The preliminary results indicate that multispectral imagery can be used to successfully detect stress at the individual tree level, but that stand density may affect results.

Keywords: CASI, detection, damage, tomentosus, health, spruce.

RÉSUMÉ

DÉTECTION ET CLASSIFICATION DES DOMMAGES CAUSÉS AUX FORÊTS PAR LA CARIE ROUGE ALVÉOLAIRE À L'AIDE D'UN SPECTROMÈTRE IMAGEUR AÉROPORTÉ (CASI)

Cette étude fait état d'un test préliminaire de l'imagerie multispectrale à 0,6 mètre pour détecter les symptômes de la carie rouge alvéolaire au niveau de l'arbre et à celui du peuplement dans une zone au centre de la Colombie-Britannique, à l'aide d'un spectromètre imageur aéroporté compact (CASI). Ce test repose sur l'utilisation d'une technique d'extraction automatisée des houppiers de conifères suivie d'une classification de l'état de santé de chacun des arbres. Les résultats préliminaires indiquent que l'imagerie multispectrale peut servir à détecter efficacement le stress au niveau même de l'arbre, mais que la densité du peuplement peut nuire aux résultats obtenus.

INTRODUCTION

Efforts to use remote sensing in the detection of damage caused by forest pathogens has received considerable attention since the mid-1950's (Murtha, 1972). Early efforts focused on variations of spectral reflectance using near-infrared sensitive films for disease detection studies. It was demonstrated that a change in reflectance occurred in the near-infrared region of the spectrum before any change took place in the visible

portion of the spectrum (Murtha, 1972). Root disease detection using the Compact Airborne Spectrographic Imager (CASI) has been identified as a new tool for the assessment of root disease incidence and areal extent. Root disease inventories are required to assist forest planning and decision making. Conventional ground surveys are labour intensive, time consuming and therefore expensive. The results of these surveys are often inconsistent and variable due to surveyor bias and the subjectiveness of visual crown rating. Ideally, an automated remote sensing approach could remove the subjectivity associated with human surveyors and provide an objective and repeatable methodology. This approach would utilize processes that enable the automated isolation of individual conifer trees followed by a tree-level health classification.

Tomentosus root rot caused by the fungus *Inonotus tomentosus* (Fr.:Fr.) S. Teng affects spruce primarily, but other conifers can be effected as well. This disease is common in spruce forests throughout the Sub Boreal Spruce (SBS) and the Boreal White and Black Spruce (BWBS) biogeoclimatic zones in British Columbia (Pojar *et al.*, 1987). Understanding the biology of the disease helps us to determine the limitations of any attempt to remotely sense stress caused by this forest pathogen.

Infection occurs by fungal penetration of small roots at points of root contact between infected and uninfected trees. Spread of the disease occurs within the heartwood of roots initially, but in time the fungus reaches the bark and kills the root. Once enough roots are killed, symptoms of stress appear in the foliage of the crown. These symptoms are in the form of: reduced height growth of the leader and branches, a general thinning appearance of the crown, chlorosis (reduced chlorophyll) of the foliage and possibly a stress induced-cone crop when symptoms have progressed to the severe stage. Symptoms are generally considered to be unreliable in the early stages of disease development.

Since root disease is spread by root contact, the resulting pattern involves the formation of pockets or canopy gaps as the disease gradually radiates out from a central area. In matures stands, a typical root disease centre is characterized by a canopy gap containing randomly oriented windthrow, one or more standing dead spruce trees and stressed trees along the advancing edge of the gap. Root disease gaps are often clustered and will coalesce in time.

The purpose of this study is to determine whether stress caused by root disease can be detected at the tree and the stand level using CASI imagery. A further objective was to determine the effect of stand density on the stress signature of individual trees.

METHODS

THE SITE

The site is located approximately 40 km Northeast of Prince George, British Columbia. The study area is centred at approximately N53° 59', W122°10'. Mean elevation of the study area is approximately 715 meters. Its terrain consists of a relatively flat bench (relief <3 m) of glaciofluvial deposits. The soil type is a District Brunisol comprised of coarse sand. It is located in the Willow wet cool Sub-Boreal Spruce biogeoclimatic sub-zone, in the sub-mesic to mesic spruce - Huckleberry - Highbush-cranberry site series (SBSwk1/05, DeLong 1996). Thimbleberry (*Rubus parviflorus* Nutt.) and black huckleberry (*Vaccinium membranaceum* Doug. Ex Hook.) are the dominant shrubby vegetation on site.

The study area is a commercial thinning trial that was established in 1986. The stand is an 80 year old fire origin hybrid white spruce (*Picea glauca* x *engelmannii* Engelm.) stand with minor amounts of interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). The stand was divided into two units; one unit (approximately 8 hectares) was thinned and the other unit of similar size was left as an untreated control. The initial density was 2000 live stems per hectare (sph) and the post thinning density was 650 sph. The entire stand was relatively uniform with respect to topography, ecosystem unit, stocking and disease incidence and extent. In 1991 a plot within each unit (Figure 1a.) was stem mapped in order to track: rate of mortality, rate of spread of disease centers, species susceptibility, and losses to growth and yield.

The plot in the thinned stratum was 4.1 hectares in size, with 2700 trees mapped. The unthinned plot was 1.1 hectares in size with 1300 trees greater than 15 centimetres DBH mapped. Attributes recorded for all trees within the plots include: tree number, species, DBH (diameter at breast height), and health class (based on visual rating of tree crown). The health class rating was comprised of the four classes: healthy, and three symptomatic classes (light, moderate and severe) based on the varying degrees of severity. A healthy tree was characterized by: good height growth resulting in a strongly conical crown, healthy green foliage, and a full crown with a normal amount of foliage retention. A severely symptomatic tree was characterized by little or no height growth resulting in a very rounded crown, chlorotic foliage (noticeably yellowed due to a low level of chlorophyll), and a thinning crown which had considerably less foliage on its branches. The light and moderate classes were simply intermediate between healthy and severe. In 1996 the following attributes were collected during the five year remeasurement: DBH (± 0.1 cm), height (± 0.5 m), and health class.

CASI IMAGE ACQUISITION AND ADDITIONAL GROUND ACTIVITIES

CASI imagery was collected on October 7, 1996 under conditions of uniform cloud cover by Itres Research Ltd. The pixel size was 0.6 meter collected at 375 meters above ground. The field of view was approximately 45° . Spectral data was collected from 8 different bands. The wavelengths of the bands are as follows: blue (450 and 500 nm), green (550 nm), orange (600 nm), red (650 nm), red edge 715 nm, and two near-infrared bands (780 and 840 nm). The image was radiometrically and geometrically corrected to a uniform elevation without the use of a digital terrain model.

Crown health ratings of over 3000 trees were conducted by a trained field crew during September and October of 1996 (in conjunction with the tree height measurement). However, it was clear from an initial inspection which compared individual tree health class ground ratings (recorded on a stem map of the trial) with the same trees on the false colour CASI image that the ground truth health ratings were inaccurate. In some instances trees rated healthy from the ground appeared severely stressed on the false colour CASI image and in other instances healthy appearing crowns on the CASI image were ground rated as 'severe'. The errors in ground truth health ratings were later confirmed through a field inspection. Two major sources of variability identified were that the illumination conditions were highly variable over the period of approximately six weeks when the ratings were made and that the ratings were made by two different observers. In order to remove both the effect of variable illumination and observer bias, the author re-rated the crowns under conditions of consistent bright illumination over a three day period in March.

An exploratory subset of training trees was selected from areas that appeared to be relatively consistently rated based on a visual comparison of the CASI image and the health ratings. These trees were used to calibrate the automated interpretation system. Approximately 15 trees per health class were identified on a paper copy 1:400 CASI map by overlaying it onto a 1:400 scale stem map of the trial area. These trees were then used to identify the mean spectrum for the four different health classes for calibrating the supervised classification.

A two step procedure was used for the derivation of health classes for individual trees. The 'green' portion of the spectrum was utilized to isolate conifer pixels in the CASI imagery. Health classes were generated based on the Infra-red (IR) and the red (R) band spectral signature. Since root rot caused stress affects the crown uniformly it allows the utilization of the mean spectrum for each individual tree in order to derive health class. Individual tree crowns were identified by applying a valley following and tree crown delineation technique developed by Gougeon (1995). Pixels within an individual tree crown were averaged to create a mean spectrum for each tree. The output product is much easier to interpret than a health classification of each individual pixel. It also provides statistics on total stems per hectare and the proportion of stems in each health class.

Once the ground truth health class was re-rated, all trees were re-visited in the field in order to create an outline of the crown perimeter onto a 1:400 scale CASI image. The tree outlines were then digitized and linked to the tree attribute file in Arc Info GIS. This step was conducted in order to create overlays for visual comparison, for measuring attributes such as individual tree crown area, and for assessing the accuracy of the tree crown delineation process.

RESULTS AND DISCUSSION

The ability to visually recognise root diseased areas in the false colour CASI imagery based on stand structural characteristics was not completely un-expected given the large scale of the paper imagery used (1:400) and the high spatial resolution of the imagery. The ability to separate between healthy and stressed trees based on spectral characteristics was considered to be the true measure of success. The "signature" of root disease was most evident in the unthinned portion of the stand. Root disease centers were easily identifiable based on the canopy gaps which typically included a dead conifer and one or more trees that exhibited a mauve or bluish-pink appearance compared to the magenta crowns of the healthy trees (Figure 1a). This was confirmed by comparing the stem map showing the location of diseased trees with the CASI imagery and also by taking the CASI imagery into the field and visually comparing the crowns of individual trees with the colour of the same crown in the CASI image. Healthy stratum were characterized by tightly spaced magenta crowns.

Table 1 shows the comparison of mean IR/R values for the four health classes. Although there is overlap between the classes, the healthy class is separable from the moderate and severe classes and only overlaps marginally with the light class. The health classes, IR/R ranges, and image colours (used in the classified image shown in Figure 1b) are shown in Table 2.

The supervised classification also showed a predictable pattern of stressed trees in and around the edge of the canopy gaps. Table 3 shows the proportion of individually separate spruce trees that were correctly classified as the same health class assigned by the visual health rating on the ground based on a sample size of 1146 trees in the thinned stratum. The percent of trees which matched perfectly was close to 50 percent for three out of four classes. Although the midpoints between the mean IR/R values of the training trees are normally used as the default values by the automated program for setting the IR/R ranges of each health class, the initial classification did not seem to 'adequately' identify the known stressed trees in the unthinned area. The IR/R ranges in Table 2 were used instead in an effort to enhance the detection of stress in the unthinned stratum. If the original midpoints had been used, the proportion of correct matches would have been considerably higher. In hindsight it is obvious that the training and the validation process need to be conducted on the thinned and the unthinned plots separately.

The comparison of the percentage of trees within each health class as rated on the ground and by the supervised classification yield another perspective. Table 4 shows the proportions of individual spruce trees rated by CASI and rated by the ground observer. From a predictive standpoint the most important class of tree is the 'severe' class as this class has the highest probability of being infected. The supervised classification predicts almost the exact same proportion of 'severes' as was observed on the ground. The next most important class is the moderate. The proportion of trees in the moderate class is overestimated considerably. The light class is also overestimated considerably. The result is an underestimation of the proportion of healthy trees. Once again, if the original midpoints (from Table 1) were used to determine the IR/R ranges as they should have been, the proportions would match much more closely.

One of the objectives of the study was to determine the effect of stand density on the stress signature of individual trees. Although the proportion of stressed trees was relatively similar in both stratum based on the ground assessment, the thinned area appears to have considerably more moderate and severely stressed trees based on a visual comparison of the two stratum in the classified image (Figure 1b). It would appear that stand density has an effect on reflectance. If density affects reflectance then any landscape level forest health assessment would have to take stand density into account.

Another result of increased stand density is the increase in the proportion of trees which are lumped together during the tree crown delineation step. A measure of this effect can be made by comparing the confusion matrix for single crowns only (Table 3) with the confusion matrix comprised of single crowns and multiple crowns that were composites of 2 to 5 crowns (Table 5). The percent of correct matches in Table 5 drops by 5 % for the severe and moderate classes, 3 % for the light and only 1.5 % for the healthy. The net effect is for the stand to appear to have fewer crowns that reliably indicate stress in the denser areas of the thinned plot. This same 'masking' of stress is expected to be far more pronounced when the unthinned stratum is examined.

Evaluating the effect of stand density on stress detection involves correctly identifying the factors which could produce this effect. Could increased stand density affect the individual mean tree spectrum? Could poor viewing conditions of the crowns in the dense stand have resulted in a bias in the ground rating of crown conditions? Could the effect of the thinning which was conducted ten years ago have resulted in more stressed trees in the thinned area? Since the data has not been summarized for the unthinned area yet this observation cannot be evaluated thoroughly at this point in time.

CONCLUSION

The preliminary results of this study indicate that an automated health classification using 0.6 m resolution CASI imagery successfully detected stress at the individual tree level. The automated interpretation classified the health of individual trees within a given stand more consistently than the visual method since the visual classification was influenced by variable illumination conditions, subjective ground rating procedure and human error. On the other hand, the effect of factors such as stand density, varying species composition, and stand age have complicating effects on classification using remotely sensed imagery. Since this study focused on one site very intensively, testing needs to be replicated on different sites which represent a wide range of operational conditions.

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Health Class	Number of Trees	Number of Pixels	Mean IR/R	Stdev IR/R
Healthy	17	510	7.08	0.80
Light	9	217	5.63	0.76
Moderate	16	316	5.12	0.68
Severe	17	347	4.42	0.81

Table 1. Comparison of mean (IR/R) values for root rot health classes

Health Class	IR/R Range	Image Colour
Healthy	> 7	dark green
Light	6 - 7	light green
Moderate	5 - 6	yellow
Severe	< 5	red

Table 2. Health class, IR/R ranges and image colours used in the supervised classification

CASI\Ground	Healthy	Light	Moderate	Severe
Healthy	23.2	8.8	2.6	0
Light	55.8	48.9	23.8	7.5
Moderate	19.9	39.0	59.6	41.5
Severe	1.0	3.2	13.9	50.9

Table 3. Confusion matrix for health class of classified single Spruce crowns in the thinned stratum (n = 1146 trees)

Health Class	Ground	CASI
Severe	4.6	5.7
Moderate	13.2	32.4
Light	32.6	47.1
Healthy	49.5	14.7

Table 4. Percent of single crowns rated by ground and by the automated classification

CASI\Ground	Healthy	Light	Moderate	Severe
Healthy	24.6	10.0	4.3	0
Light	54.8	51.9	28.8	9.8
Moderate	19.6	35.5	54.5	44.3
Severe	1.0	2.5	12.3	45.9

Table 5. Confusion matrix for health class of classified single and multiple Spruce crowns in the thinned stratum (n = 1470 trees)

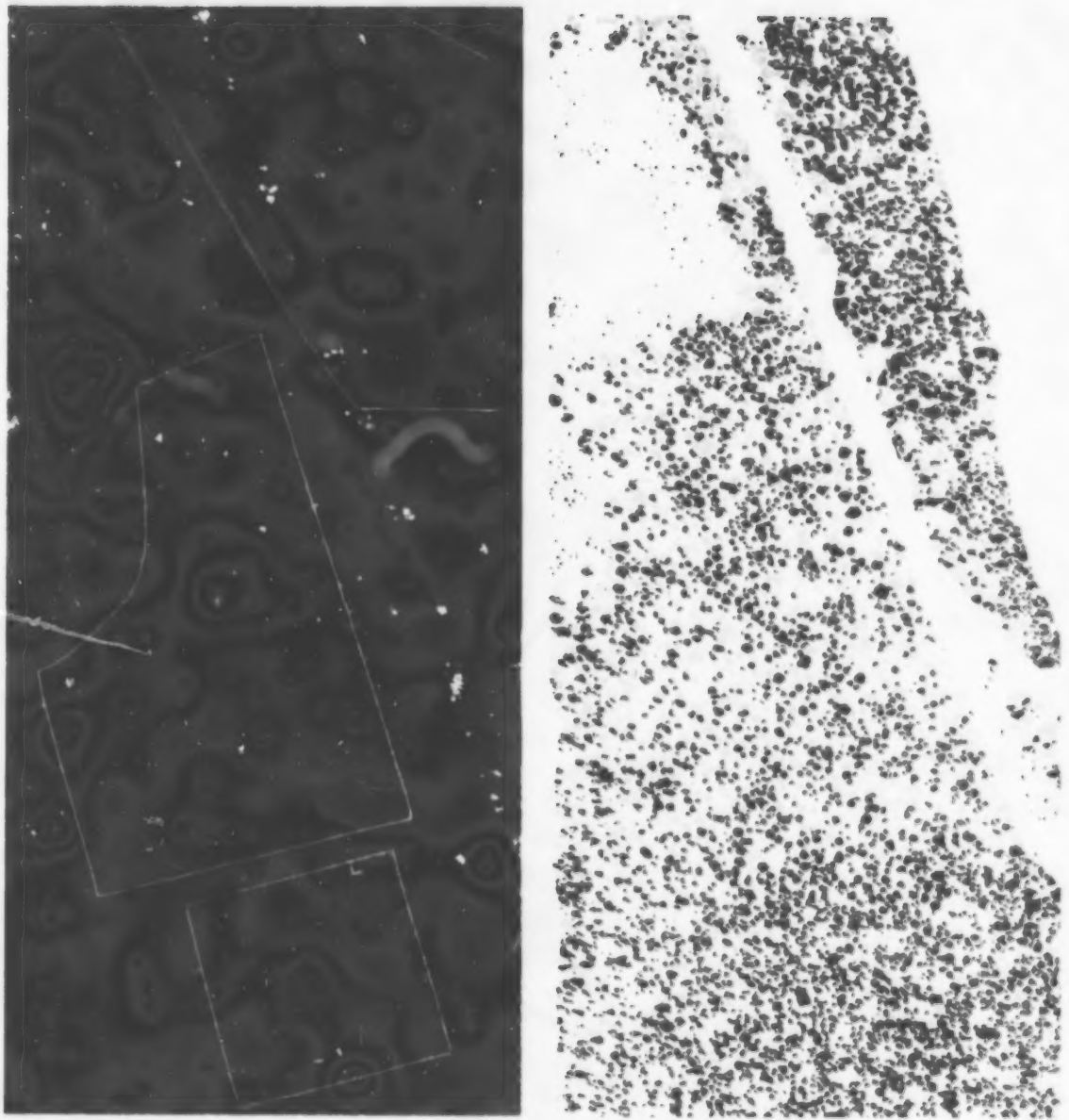


Figure 1. False Color Image (left) and Supervised Classification (right) of the Study Area.



PRELIMINARY ASSESSMENT OF *Phellinus weirii* – INFECTED (LAMINATED ROOT ROT) TREES WITH HIGH RESOLUTION CASI IMAGERY

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ABSTRACT

Root diseases caused by several endemic fungi are economically and ecologically important disturbance agents in the forests of western North America. Laminated root rot (*Phellinus weirii*) has particularly important impact in coastal Douglas-fir stands. Forest managers would like an economical survey procedure for detecting pockets of *Phellinus weirii* infected trees for the purpose of salvage, remedial activities and inventory. Aerial survey with multispectral imagers such as casi, coupled with automated detection of damaged trees may provide a cost-effective survey method.

Casi imagery in eight spectral bands has been corrected to an orthoimage and radiometric corrections for the effects of illumination and view angle applied. Trees of varying levels of root rot symptoms were assessed in the field and related to delineated trees on the imagery. Visual symptoms on the ground ranged from subtle crown shape and growth rate changes, through gradual needle loss, to mortality. Chlorosis occurred on some trees. Preliminary analysis, including classification and regression analyses of symptom classes or levels, indicates that light crown symptoms will be difficult to consistently detect. However, moderate and severe damage including needle loss (e.g., > 25%) does appear to be detectable. Isolated trees of similar characteristics as root rot infected trees do appear on the imagery in scattered locations unrelated to root rot activity. It is anticipated that these false alarms can be largely mitigated by identifying the characteristic pattern of root rot damaged trees (i.e., stressed trees around a centre, the centre often being a hole or gap in the canopy).

Keywords: *Phellinus*, root rot, damage, remote sensing, casi, Douglas-fir.

RÉSUMÉ

ÉVALUATION PRÉLIMINAIRE D'ARBRES INFECTÉS PAR LA CARIE JAUNE ANNELEE (*Phellinus weirii*) À L'AIDE DE L'IMAGERIE CASI À HAUTE RÉOLUTION

Les maladies des racines causées par des champignons endémiques ont des effets perturbateurs importants sur les plans économique et écologique dans les forêts de l'ouest de l'Amérique du Nord. La carie jaune annelée (*Phellinus weirii*) a une incidence particulièrement grave sur les peuplements de Douglas verts. Les aménagistes aimeraient pouvoir appliquer une procédure peu coûteuse de reconnaissance pour détecter les poches d'arbres

infectés par le *Phellinus weirii* à des fins de récupération, de traitement et d'inventaire. Les levés aériens à l'aide de spectromètres imageurs comme le CASI, couplés à la détection automatisée des arbres endommagés pourraient constituer une méthode rentable.

L'imagerie CASI dans huit bandes spectrales a été transformée en orthoimage et corrigée au plan radiométrique pour compenser les effets de l'éclairement lumineux et de l'angle d'observation utilisé. Des arbres de hauteurs diverses ou présentant des symptômes de carie jaune annelée ont été évalués sur le terrain et associés à des arbres délimités sur l'imagerie. Les symptômes observés visuellement au sol comprenaient des changements subtils de la forme des houppiers et du taux de croissance, en passant par la perte graduelle des aiguilles et la mortalité. Certains arbres étaient atteints de chlorose. Une analyse préliminaire, comprenant des analyses de classification et de régression des classes ou des niveaux symptomatiques, indique que les symptômes associés au rétrécissement des houppiers seront difficiles à détecter de façon constante. Cependant, les dommages moyens et graves ainsi que la perte des aiguilles (soit > 25 %) semblent être détectables. Des arbres isolés présentant des caractéristiques similaires aux arbres infectés par la carie jaune annelée apparaissent sur l'imagerie en divers endroits, mais ne sont pas associés aux infections par la carie jaune annelée. Nous croyons que ces fausses alarmes peuvent être atténuées en identifiant le modèle caractéristique des arbres atteints par la carie jaune annelée (c'est-à-dire des arbres soumis à un stress autour d'un point, le point étant souvent une trouée dans le couvert forestier).

INTRODUCTION

Root diseases are becoming increasingly important damage agents in the forests of northwestern North America. Laminated root rot (LRR) is the most important single natural disturbance causing long-term change in these forest ecosystems (Thies, 1998). LRR impacts forest productivity by reducing tree growth and by killing trees. *Phellinus weirii* (Murr.) Gilbn., the causal organism, is a native fungal pathogen which has coevolved with native coniferous species such as its principle host, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Other susceptible hosts include true firs (*Abies* spp.) and mountain and western hemlock (*Tsuga mertensiana* (Bong.) Carr. and *Tsuga heterophylla* (Raf.) Sarg.). Resistant hosts include western redcedar (*Thuja plicata* Donn ex D. Don). All hardwoods are immune to *P. weirii* infection.

The disease begins in a stand when uninfected roots of a susceptible tree contact infected stumps or roots (i.e., inoculum) left from a previous stand. Inoculum of *P. weirii* can survive in large infected stumps and roots for 50 years or longer. Once established in the roots of a susceptible host, *P. weirii* progressively causes decay, resulting in reduced uptake of water and nutrients and weakened structural support to infected roots (Thies and Sturrock, 1995). Trees of all ages are susceptible to *P. weirii* infection, although older trees are better able to withstand the damaging effects. As with other root pathogens, the damage that *P. weirii* causes to roots underground is eventually expressed above-ground in the crown. Crown symptoms caused by *P. weirii* usually develop only after the fungus has killed and decayed a significant portion of the root system. In young stands, trees growing near inoculum may develop crown symptoms and be killed within a few years of infection. In older stands, crown symptoms may appear 5 to 15 years after initial infection. Larger infected trees may live for decades after symptoms first appear, with progressively more severe symptoms and concurrent growth loss (Thies and Sturrock, 1995). Crown symptoms caused by *P. weirii* and visible from the ground include the following:

- reduced height growth in branches but especially evident in the leader; trees in decline for many years develop a rounded or dome-shaped top with crowns eventually dying
- needle chlorosis
- needle loss
- production of large numbers of stress-induced, smallish cones. Mortality can eventually occur.

Stand level symptoms evident on the ground and from the air include canopy openings which have standing dead trees, windthrown trees and crown symptomatic trees at their edges. These centres of infection expand approximately radially at about 30 cm per year (Thies and Sturrock, 1995). In coastal areas of the Pacific Northwest, patches of hardwoods such as red alder (*Alnus rubra* Bong.) often develop in LRR centres.

Information on the location and quantity of root disease is important for management planning, for inventory to assess the impact on wood supply, for salvage logging and for planning remedial activities such as stump removal and planting of non-susceptible species. It is often highly desirable to log affected trees before they lose value. The operational forester's main requirement is the detection of infected areas and individual pockets. The forester will generally follow up with site visits before executing or planning an operation. There is therefore a fairly high tolerance of false alarms. Quantification of the root disease is beneficial, but not a high priority. There are often large areas of susceptible forest, but the target (infected areas) is small, sometimes just a few trees. Effective ground surveys for detection of root rot are therefore difficult. They are time consuming, require specialized expertise and are expensive. Recent surveys in coastal B.C. have cost \$40 to \$70/ha (personal communication D. Clark, G. Fournier). A cost-effective aerial survey method would be valuable.

This study assesses the potential of automated classification methods applied to high resolution airborne multispectral imagery (casi) for assessing the level of root rot on an individual tree basis in order to detect, map and quantify laminated root rot occurrences. This investigation is complementary with an independent study (Reich and Price, 1998) examining high resolution casi data for *Tomentosus* root disease damage of spruce in the interior of British Columbia.

DATA

Imagery was acquired with the casi imaging spectrometer (Anger et al., 1994) over a test area near Nanaimo, British Columbia, Canada (49° 06' N; 124° 00' W). Two adjacent flight lines were flown September 27, 1996. The area is on the east coast of Vancouver Island within the Coastal Douglas-fir moist maritime biogeoclimatic zone. It is predominated by second growth stands of Douglas-fir aged 75 to 85 years with heights ranging from 30 to 35 m. Stands regenerated following clearcutting and have undergone varying degrees of thinning.

Data resolution is 60 cm and consists of eight spectral bands at 438 nm, 489 nm, 550 nm, 601 nm, 656 nm, 715 nm, 795 nm and 861 nm with approximately 25 nm bandwidths. Data from only one of the flight lines was used for this study. It should also be noted that similar data was acquired in November, 1995 and will be examined in subsequent analyses. Data was geometrically corrected to cartographic coordinates by Ires Research Ltd.

The data was radiometrically adjusted to take into account the effect of varying illumination and view angle conditions (i.e., the bidirectional reflectance distribution function, BRDF). Trees were automatically isolated with the valley following approach described by Gougeon (1998). A preliminary broad cover type classification of the isolated trees to identify conifer trees was then conducted. The mean value in each spectral band, derived from all pixels within the isolated tree, was taken to represent the signature for that tree. The average, within each column, of all pixels classified as conifer was plotted and a third order polynomial fit to these points (Figure 1). This created a correction curve for each band. A correction (offset) was then applied to the pixel values of each column of the image based on this correction curve. The offset was equal to the difference between the curve at that column and the curve at nadir. The mean value of trees in each column of the resulting corrected image should, therefore, all be approximately equal to the mean value at nadir. In other applications of this technique an iterative procedure is used. After the correction described above, a second classification of conifers is conducted using the corrected data, a new correction curve generated and applied. This is necessary when significant errors in the initial conifer classification occur due to the BRDF effect present in the original imagery. This additional step was unnecessary with the image used in this study. Another unique feature of the correction system is that it can be applied to geometrically corrected imagery. The imagery in essence is realigned along its edges to approximate the original column oriented non-geometrically corrected imagery.

A specialized ground survey was conducted to define root disease conditions in the study area. Sites of suspected or known laminated root rot were visited. Trees in the immediate vicinity of root disease centres and trees some distance away from centres were numbered and located on hardcopy casi images. Five sites were selected and 260 trees marked and assessed. Species, dbh and dominance were recorded for each tree. The crowns of most trees were photographed. ➤

A) percent needle loss	estimated to nearest 5%
B) chlorosis	N nil ? colouration may be a little abnormal but not definite L light chlorosis M moderate chlorosis S severe chlorosis
C) crown health class	1) Healthy (full crown, good leader and shoot growth, conical crown, no discolouration) 2) Lightly Symptomatic (reduction in shoot length; crown may be rounded, there may be slight chlorosis; little or no foliage loss or crown thinning) 3) Moderately Symptomatic (may have reduction in shoot length and rounded crown, may be chlorotic, has foliage loss and thinning of the crown foliage) 4) Severely Symptomatic (reduction in shoot length, usually with rounded crown, may be chlorotic, foliage loss and crown thinning is large) 5) Dead (100% needles loss, most branches still intact) Gradations were also included between classes.

Table 1. Crown conditions assessed in the ground survey of root disease symptoms.

An independent (i.e., without access to the *casi* imagery) assessment of the root disease condition of each of the 260 trees was conducted by experts. Three aspects of crown symptoms were assessed: percent needle loss, chlorosis level, and crown health class. Table 1 gives details of these assessments. Crown health class incorporated, in an overall assessment, needle loss, chlorosis, shoot length reduction and rounding of crown shape. It was adapted from a similar system of Reich and Price (1998) used for assessing *Tomentosus* root disease. There were few trees with signs of chlorosis in the test sites. Finally, an overall assessment of whether a tree was affected by laminated root rot was also made taking into account all available field observations. Special features of the tree that might influence its spectral characteristics were also coded on the field sheet. These include whether the trees were large, open-grown, or edge trees (i.e., at the edge of an opening). The authors have observed in other studies that such trees often have 'abnormal' spectral signatures due to more of the crown being exposed to illumination of direct sunlight. Trees judged to be exceptionally healthy and vigorous trees were noted. Snags were also recorded as was their degree of branch loss. Snags were differentiated from newly dead trees with most of their fine branching remaining and the latter were designated as having 100% needle loss. Regression analyses of band intensity values versus percent needle loss included only these 100% needle loss trees (not the snags).

DATA ANALYSIS, RESULTS AND DISCUSSION

Trees were manually delineated on the *casi* imagery and the multispectral signature for each tree was generated. This signature included the mean value in each spectral band for all the pixels within the outlined area of the tree. These were used in subsequent regression analysis and test classification.

The mean value for each tree was plotted against both needle loss and crown health class. Relationships were curvilinear for crown health class. This is to be expected as the classes are gradational with only small changes in symptoms for the light classes; these mostly being represented by changes in shoot length and crown form which may have little effect on spectral reflectance. Figure 2 shows the relationship of band intensity versus percent needle loss for selected bands. The relationship is linear. Table 2 gives the linear correlation coefficient for each band. It can be seen that the 550 nm, 601 nm and 715 nm bands had poor capabilities for differentiating damage levels; the 438 nm, 489 nm, 656 nm, 795 nm and 861 nm bands had moderate relationships. The 656 nm band had the highest correlation, followed by the blue and then near-infrared bands. Ratios of bands were also investigated (Figure 2; Table 2). The ratios improved the relationships. NDVI (795

nm - 656 nm)/(795 nm + 656 nm) proved the best with an r^2 of 0.84; the red over green band ratio (656 nm)/(550 nm) was also good.

Bands (nm)	r^2	Band Ratios (nm)	r^2
438	0.33	795/656	0.68
489	0.32	795/550	0.68
550	0.05	795/489	0.71
601	0.19	656/550	0.78
656	0.38	656/489	0.26
715	0.00	(795-656)/(795+656)	0.84
795	0.28	-	-
861	0.26	-	-

Table 2. Correlation coefficients of band intensity versus percent needle loss.

Because of the limited number of ground truthed trees examined in this preliminary study, a test classification of the manually delineated trees was conducted using all trees to generate the class signatures. Each tree contributes one value (mean of all pixels) for each band. Classes were healthy, light, moderate, severe and dead. The classes were based on crown health class. Dead consisted of 100% defoliated trees, but no snags. A maximum likelihood classification was then conducted on the trees using all bands except the 438 nm band which was somewhat noisy. Figure 3 gives the classification results and the ground truth tree classes for comparison. For the 73 trees tested, accuracy was 77% overall by individual tree and 88% by class average. Results should be treated with caution as they are the same trees as were used to generate the classification signatures. Dead, severe and moderate classes had little confusion, but light and healthy were confused by 12 to 27%. Some light and healthy trees were classified as moderate (7 % and 13%, respectively).

To get a better indication of expected results for operational surveys the classification was conducted on automatically isolated tree crowns. The signatures from the manually delineated trees were used to represent the classes. The trees were isolated using a valley following approach (Gougeon, 1998). Figure 4 gives the results for a segment of the flight line. Several zones of damaged trees are evident. Reconnaissance inspection of these sites indicated that many were associated with root disease, however, others may be related to other possible stresses. Isolated trees of light and to a lesser extent moderate damage are scattered within the image segment. Again, a sample of trees were checked and some were found to be affected by root disease, while others did not appear to be.

Results suggest that there may be quite a few spurious trees identified as the light damage class and using the light class on its own as a root rot indicator may result in too many false alarms. However, the characteristic pattern of damage will be useful for narrowing the zones and trees that potentially have root disease. This pattern consists of affected trees concentrating about a centre (the centre often being an opening in the canopy) with the severity of tree symptoms decreasing away from the centre. Visual scanning of the single tree classification results would be a simple procedure for identifying likely root disease centres and eliminating some false alarms. With further development, automated procedures to utilize this pattern could be created. Foresters are willing to accept a fair number of false alarms; the importance of not missing an infected area is high. Therefore, it may not be desirable to try to eliminate too many lightly affected trees in the classification. As well, accurate quantification of the level of damage on a trees basis is often not mandatory; it is the presence and location of a root rot centre and its size or number of affected trees that is important.

When applied with the single tree isolation algorithm some additional problems occur. Several trees may be combined into one tree or a single large tree broken into more than one crown. Both these types of errors can result in poor classifications of those crowns. As well, the isolation routine because it is based on outlining bright areas around darker (shaded) areas, can create "trees" in non-forest areas. A spectral classification prior to or after the isolation is used to eliminate these as much as possible. This was done in this study. A general conifer tree class separated most healthy and damaged trees from other non-tree isolated features. However, the spectral characteristics of some severely damaged trees were similar to various non-tree isolated areas. It was difficult to separate these areas from severely damaged trees without also eliminating the damaged trees.

Erroneous damaged trees therefore may appear in open areas. Again, this problem may be resolved simply by visual inspection or more sophisticated techniques, but it does demonstrate some of the considerations for operational use of the methods described above.

Further work will involve view/illumination angle (BRDF) correction of the second flight line of *casi* data and radiometric normalization to the data used in this paper. The data of the two lines can then be analyzed together and all the field sites used. Further testing with the automatically isolated trees and the 1995 *casi* data is in order. The quantitative accuracy will be tested, but a key parameter will be the degree of false alarms generated and, of course, acceptance of the methods by the operational forester as a potential useful and viable tool.

CONCLUSIONS

Results of this study are promising in terms of identifying trees moderately or severely affected by root disease with automated isolation and classification techniques applied to high resolution *casi* or similar multispectral imagery. Dead trees are also well differentiated. There are spectral differences in the 438 nm, 489nm, 656 nm, 795 nm and 861 nm bands. Ratios of bands were notably better than the single bands, in particular an NDVI and 656 nm/550 nm ratio. With the data tested, moderate and severe symptoms had good detection. Light crown symptoms may, however, be difficult to consistently detect. There may be considerable numbers of false alarms in terms of scattered trees identified as infected. It is anticipated the false alarms can be mitigated by using the pattern of damaged trees characteristic of root disease centres, either visually or in an automated procedure. Further testing is needed to prove the results and test the viability of the methods.

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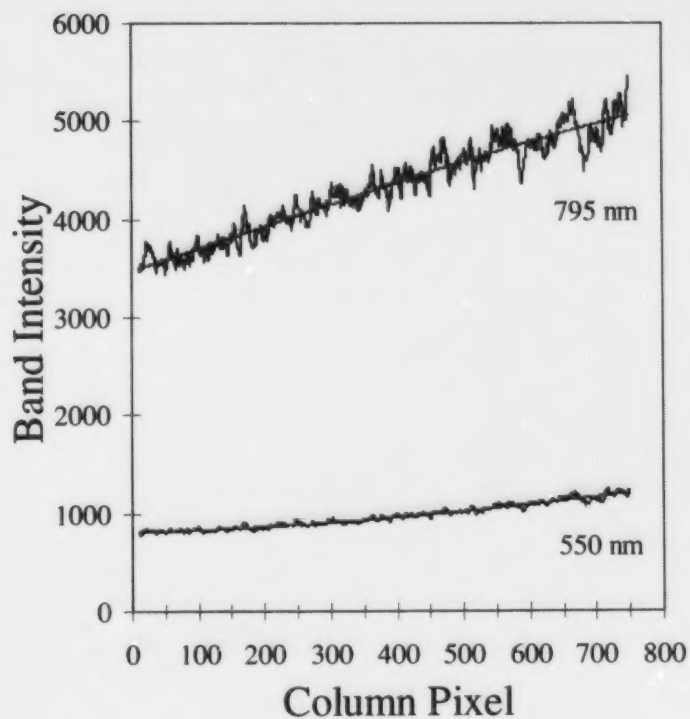


Figure 1. Combined effects of illumination, view angle, and atmospheric conditions on the imagery. The column average of pixel values under a mask representing the automatically delineated conifer trees are plotted along with a third order polynomial correction curve fitting these data.

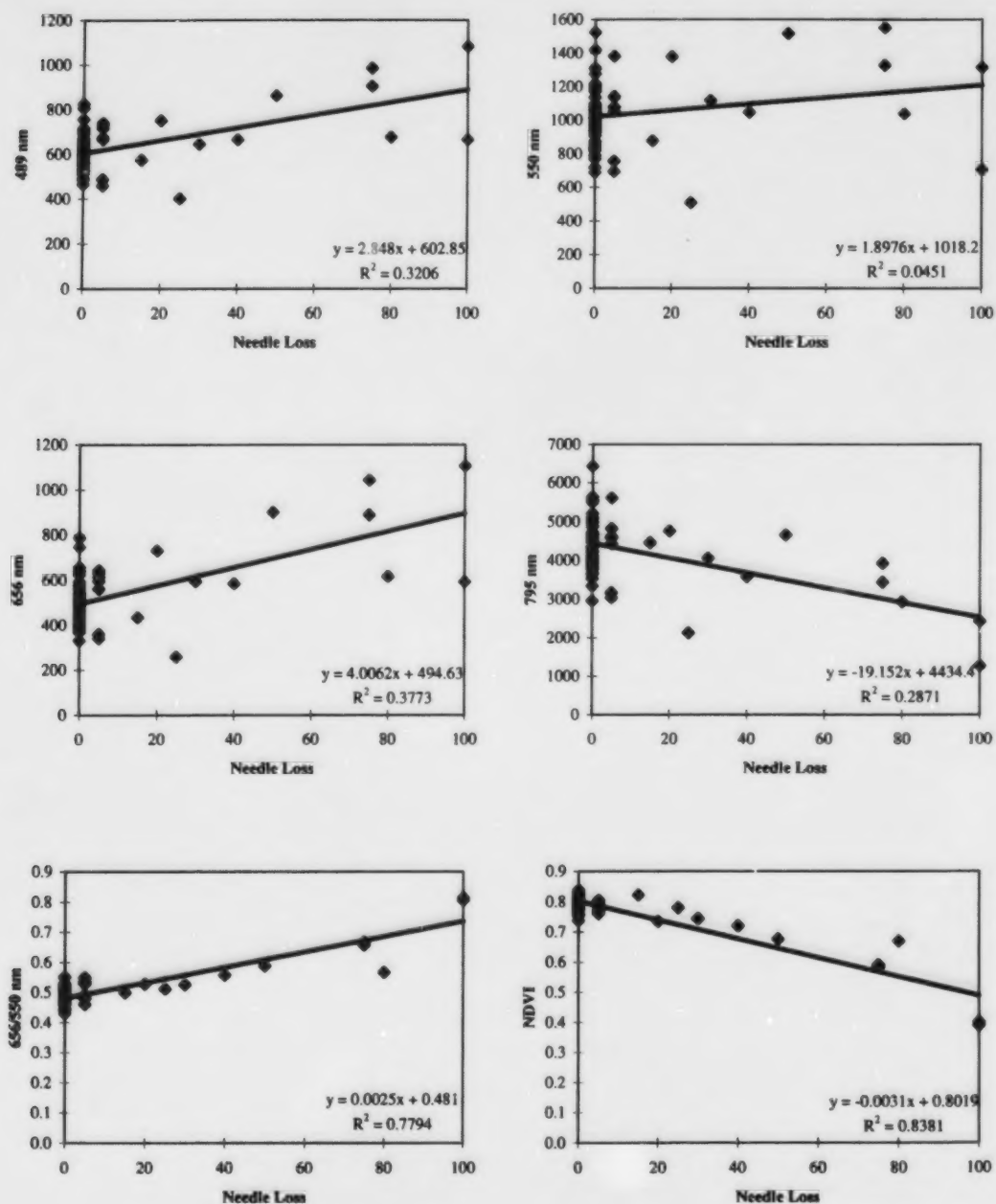


Figure 2. Band intensity versus percent needle loss for ground truth trees with a straight-line regression fit plotted.

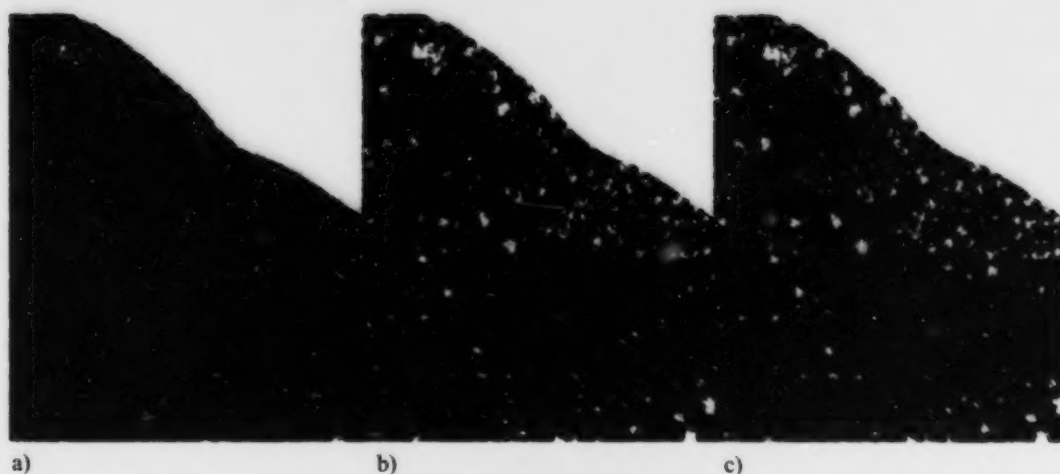


Figure 3. Classification results for ground truth trees. a) colour infrared band combination, b) ground truth trees manually delineated and ground truth class colour coded (healthy = dark green; light = light green; moderate = yellow; severe = orange; dead = red), c) classification results for ground truth trees.

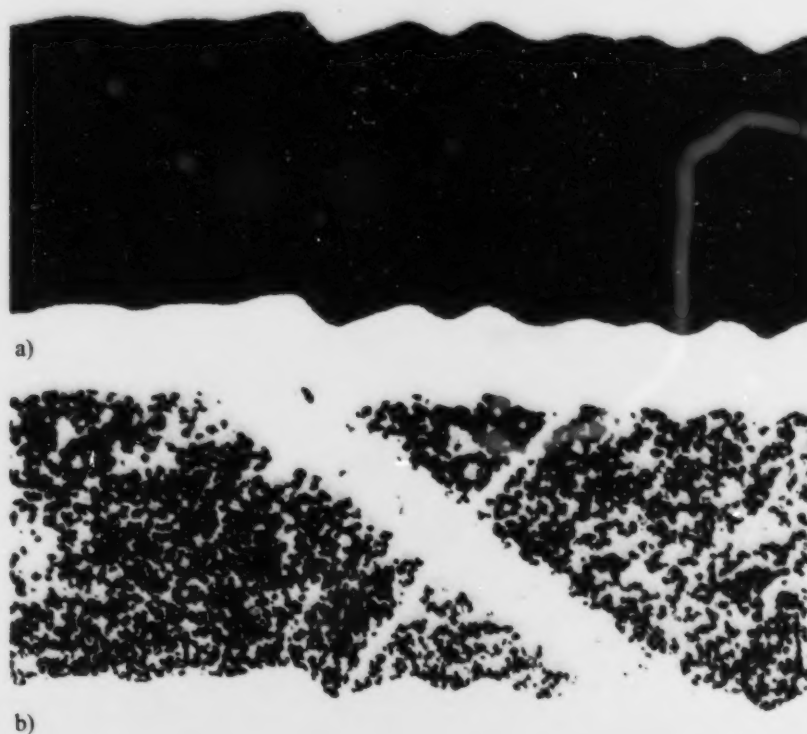


Figure 4. Classification results on automatically isolated trees for an approximately 750 m long image segment. (dark green = healthy; light green = light; yellow = moderate; orange = severe; red = dead)



Species Classification

ALGORITHMS FOR STRUCTURE- AND CONTOUR-BASED TREE SPECIES CLASSIFICATION USING DIGITAL IMAGE ANALYSIS

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ABSTRACT

Two methods useful for characterising certain patterns of individual tree crowns are presented. They could be applied in an automated image analysis system for tree species classification in digital high spatial resolution aerial images. The structure-based measure made use of the internal structure of individual tree crowns in the intensity image. The contour-based measure utilized the visible crown edges and their grey level curvature values.

The thresholded Laplace transform at a selected degree of smoothing was used for extracting the internal pattern. Skeletonization was used for data compression and to enhance features to be used in the subsequent analysis. The resulting skeleton branches were one pixel thick but they still contained the structural pattern that was identified by the Laplace transform. The skeleton was split into simple segments without branches. The orientation of each individual segment in the tree crown was calculated. A Hough transform technique was developed for analysing whether they collectively had a dominating radial structural behaviour. This method could clearly discriminate between *Picea abies*, with a typical radial pattern, and *Pinus silvestris* and *Betula sp.*

The contour-based method was based on the gray level curvature values on the crown edges. The contour-based measure could possibly discriminate between non-smooth contours (often in our images *Picea abies* and *Populus tremula*) and smooth contours (often *Pinus silvestris* and *Betula sp.*).

Keywords: aerial image, crown structure, gray level curvature, pattern recognition, texture, tree species classification.

RÉSUMÉ

ALGORITHMES DE CLASSIFICATION DES ESPÈCES D'ARBRES BASÉE SUR LA STRUCTURE ET LES LIGNES DE CONTOUR AU MOYEN DE L'ANALYSE D'IMAGES NUMÉRIQUES

Le présent rapport traite de deux méthodes utilisées pour caractériser certaines formes de houppiers. On peut envisager de les mettre en œuvre dans un système automatisé d'analyse d'images aux fins de la classification des espèces d'arbres apparaissant sur des images numériques aériennes à haute résolution spatiale. On a effectué la mesure fondée sur la structure en observant la structure interne des houppiers fournie par l'image d'intensité, tandis que la mesure basée sur les lignes de contour reposait sur l'observation des contours visibles des houppiers et les valeurs correspondantes des courbes des niveaux de gris.

Pour extraire les formes internes, on a appliqué la transformée de Laplace avec un seuillage et un degré déterminé de lissage. On a également eu recours à la squelettisation en vue de comprimer les données et d'accentuer les caractéristiques destinées à l'analyse subséquente. Les branches du squelette ainsi obtenues étaient de la largeur d'un pixel, mais présentaient tout de même la structure identifiée par la transformée de Laplace. Le squelette a été divisé en segments simples sans branches. On a ensuite calculé l'orientation de chacun des segments de houppier, puis on a mis au point une technique de transformation, dite de Hough, afin de déterminer s'il se dégageait un comportement structurel radial dominant pour l'ensemble des segments. Grâce à cette méthode, il a été possible de distinguer l'épicéa commun (*Picea abies*), caractérisée par une structure radiale type, du pin sylvestre (*Pinus silvestris*) et du bouleau (*Betula sp.*).

Pour la méthode basée sur les lignes de contour, on a analysé les courbes de niveaux de gris représentant les contours des houppiers. On estime que cette mesure pourrait permettre de discriminer les contours non lisses (souvent représentatifs du *Picea abies* sur notre image) des contours lisses (souvent représentatifs du *Pinus silvestris* et du *Betula sp.*).

INTRODUCTION

In Sweden, field work and medium-scale aerial photo-interpretation are the dominating methods for collecting forest resource data. However, large-scale aerial photography of sample plots, for estimating tree crown closure or size and species composition, is not widely known to be used in the Nordic countries. In Canada, such systems are in operational use (Spencer & Hall, 1988). This type of high spatial resolution aerial images has so far been analysed by visual/manual methods.

Tree species classification based on internal crown structure needs an image data quality that is able to resolve the typical tree crown texture of the species. The crown of a mature Norway spruce (*Picea abies* (L.) Karst) is often made up of radially organized branches while a mature Scots pine (*Pinus silvestris* L.) and birch (*Betula sp.*) often have a more homogeneous crown with no dominating radial structure (see Mitchell and Wilkinson, 1977, for a sketch). The smoothness of the visible contours are often a characteristic feature. Birch and mature Scots pines have often very smooth contours. The three species are the overwhelmingly dominating species in the Scandinavian forests.

The purpose of this work was to develop and describe two different pattern recognition techniques utilising the different crown structural characteristics of individual trees in the high spatial resolution images (pixel size 10 cm). This paper describes the mathematical and computational background.

MATERIAL AND METHODS

IMAGE PROCESSING AND ANALYTICAL BACKGROUND

Healthy vegetation reflects most of the near IR part (wavelength 700 - 1500 nm) of the sunlight (Harris, 1987). In addition, stressed or senescent vegetation has a lower near infrared reflectance. Branches in full sunlight reflect more than branches in shadow.

The background is often dark in the aerial CIR image due to tree shadows and nonvital vegetation in the shade. Furthermore, the crown surface of a tree is rather rough. This makes the reflectance quite irregular and the image will depict different crown patterns. One way to extract these structures in the image is to compute image derivatives in specified directions. The second order derivative, measured as the digital Laplace transform, is a measure of the rate of change of the first derivative in two perpendicular directions, x and y (Gonzales & Woods 1992). It is a sum of the second order partial derivatives (Lindeberg, 1994):

$$\nabla^2 L = L_{xx} + L_{yy} \quad (1)$$

where L is the appropriate smoothed image. This transform is sensitive to abrupt changes and it will enhance reflectance edges in the monochrome image. The transform is zero on a flat surface or on a long, smooth grey tone ramp in the image. Thresholding of equation (1) ($T=0$) splits the image in one region for positive values and one for the negative values. One of them (negative values) corresponds to the visible branches.

A distance transform of a region is a measure of the minimum distance between each pixel in the region and the border of the region. In this work, a (3,4)-distance transform (Borgefors, 1986) was computed on the thresholded digital region. It utilises different weights (3 or 4) depending on the step direction (horizontal/vertical or diagonal) in the digital image.

Skeletonization reduces a region that is several pixels wide, yielding one pixel wide axial representation. In this study, a well-shaped, stable and reversible skeletonization algorithm (Sanniti di Baja, 1992) was used on the (3,4)-distance transform. In this case, with a thresholded Laplace transform, the skeleton identifies the structure of the dominating region where high values of the Laplace transform occurs.

The Hough transform (Gonzales & Woods, 1992) detects structural relationships between pixels in an image. For instance, straight lines and circles may be detected. Consider a point (x_i, y_i) on a straight line in the image. There is an infinite number of continuous lines that pass through this point. All these lines satisfy the equation $y_i = ax_i + b$, for different values of (a, b) . If the equation is stated as $b = -x_i a + y_i$, the equation is for a single line in the parameter space (ab -plane) for a specific point (x_i, y_i) . A second point (x_j, y_j) , on the same line in the image, will also have a line in the parameter space and it will intersect the first line at (a', b') . This is true for all points on the line in the image. The parameter space can be subdivided and the resulting so-called accumulator cells will be incremented by one for every line in the parameter space that crosses it. A cell with a high value indicates the presence of a line in the original image with parameters (a', b') . The Hough transform could be adapted for many different practical situations. It can also be simplified, using a one-dimensional parameter space, or it can detect more complex shapes and patterns using a modified multi-dimensional parameter space (e.g., Han et al., 1994).

The orientation of a feature in an image is useful in a pattern recognition algorithm. Several parameters can be used, but a simple method is to make use of a centroid. The net minimum moment axis of a feature is the line around which the feature would have the lowest moment of rotation (Russ, 1995).

The orientation of the net moment axis was given by

$$\theta = \tan^{-1} ((M_{xx} - M_{yy} + \sqrt{(M_{xx} - M_{yy})^2 + 4 \cdot M_{xy}^2}) / (2 \cdot M_{xy})) \quad (2)$$

where M_{xx} , M_{yy} , and M_{xy} are the moments around the x - and y -axis and the line $y=x$, respectively. They were given by

$$M_{xx} = S_{xx} - (S_x^2 / \text{Area}) \quad (3)$$

$$M_{yy} = S_{yy} - (S_y^2 / \text{Area}) \quad (4)$$

$$M_{xy} = S_{xy} - (S_x \cdot S_y / \text{Area}) \quad (5)$$

where $S_x = \sum x_i$, $S_y = \sum y_i$, $S_{xx} = \sum x_i^2$, $S_{yy} = \sum y_i^2$, $S_{xy} = \sum x_i y_i$ and $\text{Area} = \sum \text{segment pixel}_i$. The subscript i refers to the pixel within the current segment.

EDGE DEFINITION AND GREY LEVEL CURVATURE

The edges (zero-crossings) can be defined using equation (1) (Lindeberg, 1994). The edge pixels are those where the Laplacian changes sign and the gradient magnitude is high.

The gray level curvature of the intensity images is defined as (Lindeberg, 1994):

$$\kappa = \frac{L_y^2 L_{xx} - 2L_x L_y L_{xy} + L_x^2 L_{yy}}{(L_x^2 + L_y^2)^{1.5}} \quad (6)$$

where L is the smoothed image and the subscript x and y refers to partial derivatives along the x - and y -axis. The numbers are powers.

SELECTION OF DEGREE OF IMAGE SMOOTHING

The degree of smoothing of the aerial images was based on the generalised entropy function of order $\alpha=5$. It is defined as minus the logarithm of the expected $(\alpha-1)$ -norm (Sporring and Weickert, 1997):

$$S_\alpha(p) = \frac{1}{1-\alpha} \log \sum_i p(i)^\alpha \quad (7)$$

where the probabilities $p(i)$ are based on the interpretation of images as spatial distributions. This can be viewed as spatially distributed light quanta and the corresponding probability was given by (Sporring, 1996):

$$p(x) = \frac{I(x)}{\sum_{x \in \text{image}} I(x)} \quad (8)$$

A first order effect to expect from simple textures, e.g., branches in a forest, is that the point of maximal entropy change should correspond to the size of the dominating image structures (Sporring, 1996). Thus, this point or a similar local point on the generalised entropy function in scale-space was used as the selected degree of smoothing.

IMAGE DATA SET

A data set of 50 colour infrared aerial images (Kodak Aerochrome Infrared Film 2443) was acquired in central Sweden (62°27'N, 16°55'E) on August 10, 1995. The image scale was approximately 1:2000 (focal length: 302.97 mm, flight height 600 m) and their original size was 23 X 23 cm. The spatial resolution of the photographic film was approximately 0.1 m. These images depicted mature Scots pine, Norway spruce, birch and some aspen. Tree crowns were manually segmented after identifying their outer contours for the structure-based process. The pixel size was 10 cm and the image size was 120 m.

The algorithms was implemented in the UNIX-based Khoros 2.1 software package.

DEFINED STRUCTURE-BASED MEASURE

Two different metrics were defined. They were measurements of the crown patterns to conclude if there were any dominating radial structures or whether there were smooth or non-smooth visible contours. This section describes how these two metrics are calculated from the subimages of the tree crowns or possibly in a region of interest (ROI) in the large image.

The Laplace transform (equation (1)) was calculated on the intensity subimage. $T = 0$ was selected as a threshold and a digitized pattern (region) in the image was identified by the Laplace transform. The pattern described the position of the visible branches.

The second procedure involved computing a skeleton of the thresholded region. This was accomplished after the (3,4)-distance transform was calculated from the background into the region. The resulting skeleton was split by removing skeleton branch points and their eight neighbours. (See Sanniti di Baja, 1992, for a definition of branch point.). Single skeleton pixels were also removed. What remained were small, unconnected segments one pixel wide with different shapes and orientations.

Finally, the skeleton pattern was analysed according to the main principle: dominating radial structure (see Figure 1 (left) for a sketch).

A modified Hough transform algorithm was developed and implemented for the radial measurement. The centroid in the xy-plane of the whole skeleton pattern was the basis for the algorithm. It was computed as the average value of x and y for every pixel included in the whole skeleton pattern. One raster scan inspection was made for the whole split skeleton image. For every skeleton segment, a radius was drawn from the pattern centroid to the current segment centroid. The net minimum moment was computed and the smallest angle between 0° and 90° was calculated between these two lines. A one-dimensional accumulator, divided into nine groups (10° intervals) of the angles from 0° to 90° , was incremented in the appropriate cell by the number of pixels in the current segment. Then the next skeleton segment was considered. When the raster scan was finished, the accumulator cells were normalised by the total number of increments in the array. The result could be presented in a histogram and further analysed regarding the shape of the graph.

A further analytical step fulfils the intention of automation. A mean-angle group of the histogram was calculated as the group number where the centre of mass of all the increments was located. The lower the value was, the more radial the pattern.

Summary of the structure-based approach

- Step 1. Compute the Laplace transform (equation (1)) of the infrared layer and threshold at zero.
- Step 2. Compute the (3,4)-distance transform of the specified thresholded region.
- Step 3. Compute the skeleton from the distance transform, including some pruning.
- Step 4. Split the skeleton into unconnected segments by removing branch points and their eight neighbours.
- Step 5. Calculate the angle of the net minimum moment (equation 2) for each segment.
- Step 6. Compute the radial measure histogram.
- Step 7. Calculate the shape measure from the histogram and make a decision on species.

DEFINED CONTOUR-BASED METRICS

The contour-based measure was defined as:

$$K = \frac{\sum_i L_v^3 \times \kappa}{\sum_i |L_v^3 \times \kappa|} \quad (9)$$

where L_v is the gradient magnitude. It is raised to the power of three and used as a weight. Close to the crown contours the gradient magnitude was expected to be high. Inside the tree crowns it was expected to be a fairly small number.

The equation (9) is based on the fact that the total sum of the curvature values (including the sign) along a simple closed curve (see the second and third sketch in Figure 1) is 2π (do Carmo, 1994). The denominator will increase more than the nominator if there are a lot of mixed signs of the curvature. The second sketch (in Figure 1) will have $K=1$ and the third sketch will have $K \ll 1$.

RESULTS

The available aerial images were used in the evaluation of the algorithm (see Brandtberg, 1997). The radial measures, using the modified Hough transform technique, were computed on the split skeleton patterns for 30 test images of different species. Figure 2 shows a Norway spruce and the corresponding sub-images. Table 1 shows the average angle group for all ten test images of each species. The spruce had a lower mean value than the pine and birch. This implied that the spruce pattern was more radially organised than the others.

The radial measure was, at least for our test set, more discriminating than another defined measure, called the parallel measure.

Species	Parallel measure			Radial measure		
	Min	Mean	Max	Min	Mean	Max
Scots pine	1.8	3.0	5.2	3.9	4.2	4.5
Norway spruce	1.4	2.6	5.5	3.1	3.4	3.8
Birch	1.3	3.7	8.0	3.8	3.9	4.1

Table 1. Parallel and radial measures for Scots pine, Norway spruce and birch. The table includes the minimum, mean and maximum values found for all the ten tree crown images of each species (from Brandtberg, 1997).

The degree of smoothing was selected using the generalised entropy theory applied on the original image of the aspen in Figure 4. The smoothing levels were $\sigma_1=2.12$ and $\sigma_2=5.47$, respectively. Figure 4 shows the two different degrees of smoothing.

The same smoothing levels were used for the birch image in Figure 6. The K values (equation 9) for the aspen were 0.21 and 0.36 for the two selected degrees of smoothing, respectively. The K values for the birch image were 0.41 and 0.55, respectively.

CONCLUSION

Structure measurements of tree crown patterns were extracted from high spatial resolution aerial photographs using a suite of image processing procedures. Two different procedures were presented. The radial measure indicates that it was able to discriminate undamaged spruce crowns and the contour-based measure indicates that it is able to resolve different features of the contours. The measure was able to indicate the smoothness and non-smoothness of the two images.

DISCUSSION

The methodology, which reduces a structural pattern by creating a skeleton for further analysis, was found to be a powerful and interesting way of species classification.

In a forest there are a lot of broken, leaning and crowded tree crowns and they will complicate the tree species classification. The different tree crown patterns may vary a lot, and in the worst case a pine pattern may look like a spruce pattern.

The colour or the amount and distribution of reflected IR light may support a classification. The latter is an important feature that is able to discriminate deciduous forest (e.g., Päivinen & Rautiainen, 1990). Simple parameters could provide important image features, although some of them might depend on the specific lighting conditions.

The tree crown patterns are probably influenced by the sun inclination angle. The influence of the image scale and development of new measures of structural features should be addressed. This may include advanced statistical methodology for classifying tree species.

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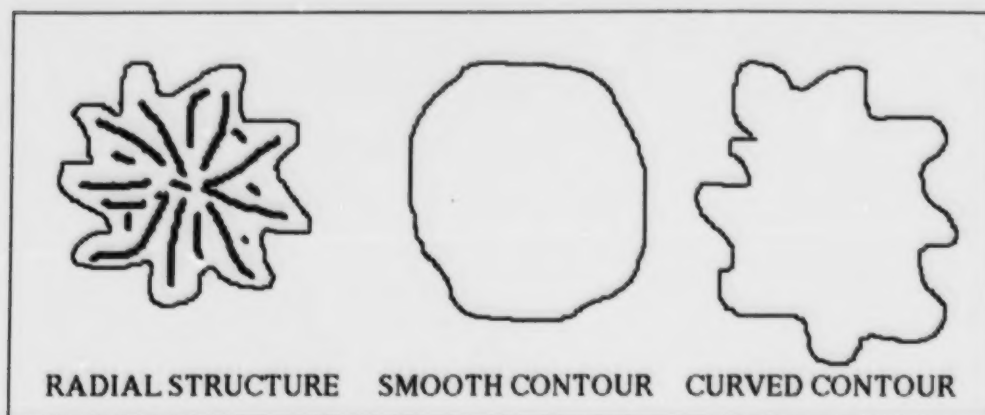


Figure 1. Sketches of a radial structure, a smooth contour and a curved contour.



Figure 2. Example of a Norway spruce and the corresponding pattern. The left image is an intensity image, the middle image is a thresholded Laplacian image and the right image is the corresponding skeleton.

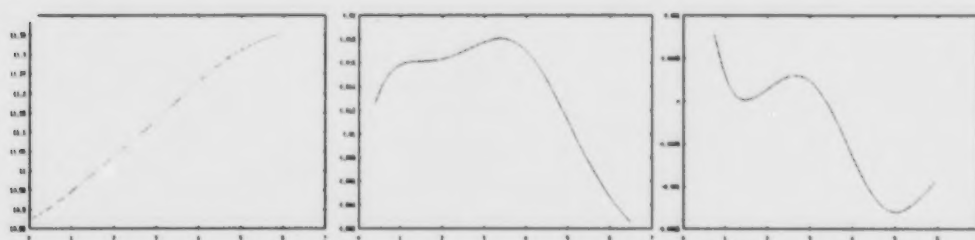


Figure 3. The generalized entropy function (left) for the original image of aspen in Figure 4. The first derivative (middle) of the generalized entropy function. The second derivative (right) of the generalized entropy function. Note the flat part of the first derivative and the maximal value of the first derivative.

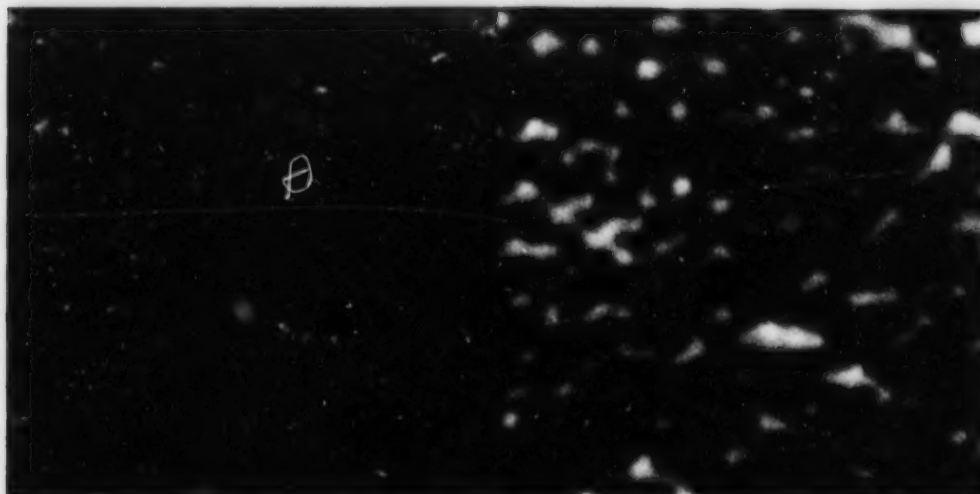


Figure 4. (left) and **Figure 5.** (right). Aerial image of aspen (left) smoothed with $\sigma = 2.12$ and the same image (right) smoothed with $\sigma = 5.47$. Both degrees of smoothing are represented by specific points in the first derivative of the generalised entropy function.

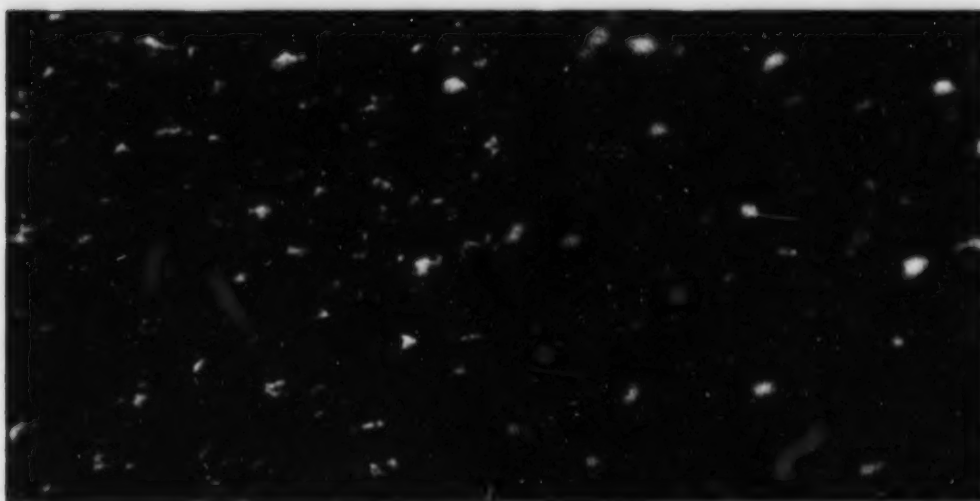


Figure 6. (left) and **Figure 7.** (right). Aerial image of birch (left) smoothed with $\sigma = 2.12$ and the same image (right) smoothed with $\sigma = 5.47$. Both degrees of smoothing are represented by specific points in the first derivative of the generalised entropy function.

INDIVIDUAL TREE CROWN SPECIES RECOGNITION: THE NAHMINT STUDY

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ABSTRACT

The species content of forest stands is an information of paramount importance in conventional forest inventories. Typically, the stands and their content are assessed by human interpretation of aerial photographs. However, using remotely sensed aerial images or digitized aerial photographs of high spatial resolution (10-100 cm/pixel), it is now becoming possible to automatically delineate most of the visible individual tree crowns (ITC) in such images. This led to the development of several ITC multispectral signatures and of an ITC-based supervised classification system making possible ITC species recognition. The resulting information on the individual trees can be preserved, where very detailed information is needed; or collated, to generate very precise information on existing forest stands, or regrouped (statically or dynamically) using new criteria, to help with multi-resource forest management.

This paper primarily addresses the species recognition aspects of this new paradigm for generating precise information useful to forest inventories. The ITC-based delineation and classification system is tested with a geometrically corrected 60 cm/pixel *casi* image of the Nahmint Lake species demonstration area, Vancouver Island, British Columbia. Simple correction curves to compensate for bi-directional reflectance function (BRDF) effects were applied to the multispectral image in spite of the fact that the image had been previously geometrically corrected by the supplier. The ITC-based supervised classification of five western Canadian coniferous species and a generic hardwood class led to an overall classification accuracy of 59.8% when tested with a conventional confusion matrix approach. These low classification results are attributed to the lack of purity of the training and testing areas. A comparison of the species content of more sizable testing areas with their corresponding field transects led to an overall error of 12%, 19.5% when only the dominant species is considered. The paper concludes with a discussion of the research and operational problems to be resolved before the goal of semi-automatic generation of precise forest management inventories is achieved.

Keywords: forest inventory, remote sensing, image analysis, individual tree crown, species recognition, *casi*.

RÉSUMÉ

RECONNAISSANCE DES ESPÈCES À PARTIR DE L'ÉTUDE DES HOUPPIERS : L'ÉTUDE NAHMINT

L'information sur les espèces qui composent un peuplement forestier est cruciale pour la réalisation d'inventaires forestiers classiques. L'évaluation des peuplements et de leur composition s'effectue généralement

par interprétation humaine de photos aériennes. Cependant, grâce aux images aériennes de télédétection et aux photos aériennes numérisées à haute résolution spatiale (10-100 cm/pixel), on commence à pouvoir délimiter la plupart des houppiers (ITC, pour Individual Tree Crown) qui apparaissent sur ces images. Ces progrès ont mené à la détermination de plusieurs signatures spectrales pour les ITC et à la mise au point d'un système de classification dirigée basé sur les ITC aux fins de la reconnaissance des espèces. L'information ainsi obtenue sur les arbres individuels peut être conservée pour répondre aux besoins en information très détaillée. Elle peut également être interclassée, en vue de générer une information de haute précision sur les peuplements forestiers existants, ou encore être regroupée (de façon statique ou dynamique) en fonction de nouveaux critères afin de contribuer à la gestion forestière à objectifs multiples.

Le présent rapport porte principalement sur les aspects de la reconnaissance des espèces à partir de ce nouveau modèle de génération d'informations précises et utiles à la réalisation d'inventaires forestiers. Le système de délimitation et de classification axé sur les ITC est mis à l'essai à l'aide d'une image de 60 cm/pixel ayant subi une correction géométrique et captée par spectromètre imageur aéroporté compact (CASI) au-dessus de la zone de démonstration du lac Nahmint sur l'île de Vancouver, en Colombie-Britannique. Pour compenser les effets de la fonction de réflectance bidirectionnelle (BRDF), on a appliqué à l'image des courbes de correction simple, même si elle avait déjà été géocorrigée par le fournisseur. Mise à l'essai avec une matrice de confusion classique, la classification dirigée basée sur les ITC de cinq espèces de conifères et d'une classe générique de feuillus de l'Ouest canadien a obtenu une exactitude globale de classification de l'ordre de 59,8 %. Ces résultats peu concluants sont attribuables au manque de pureté des zones d'entraînement et d'essai. En comparant la composition des espèces de zones d'essai plus vastes avec les transects correspondants établis au sol, on a obtenu une erreur globale de 12 % et de 19,5 % lorsque seules les espèces dominantes ont été prises en compte. Le rapport présente en conclusion les problèmes opérationnels et les problèmes propres à la recherche qu'il convient de résoudre avant de pouvoir générer de façon semi-automatique des inventaires précis aux fins de l'aménagement forestier.

INTRODUCTION

Representing 10% of the world's forests, Canada's forested lands cover 417.6 million hectares, 57% of which are considered commercial forests (Natural Resources Canada, 1996). Even though only 119 million hectares are currently managed for production, the continuous assessment and monitoring of this renewable resource represents a substantial task. Existing management inventories consist of mapping forest stands and their content from aerial photo interpretation (at the 1:10,000 to 1:20,000 scales), plus volume estimates derived from field sampling and stratification (Leckie and Gillis, 1995). Throughout Canada, whether by government or industry, 24 million hectares are mapped every year. So far, digital remote sensing has not been able to supply information at the required level of detail. In addition, modern management inventories, meant to manage the forest resource in accordance with much stricter rules taking biodiversity, wildlife, environmental and recreational concerns into account, require even more details. Fortunately, with the advent of higher resolution images, forestry digital remote sensing is presently going through a change in paradigm.

The high spatial resolutions of images available from multispectral airborne sensors, digitized aerial photographs and upcoming earth observation satellites imply a shift from the pixel-based classifications and area-based segmentations typically used at lower spatial resolutions to an "individual tree crown" (ITC) based analysis. Given that crowns are visible in these images, it is especially important for computer analysis tools to deal directly with this essential structural element. Forest stands, a higher level concept, can be tackled later, as a post-processing operation. The ITC-based approach consists of separating the crowns from one another and from the background vegetation, recognizing one by one their species and, if needed, regrouping the crowns into forest stands. It is an important initial step towards the semi-automatic production of forest inventories in which the species composition of stands or environmental strata could be identified with precision. Other important forestry parameters such as tree crown diameters, canopy closure, stem density, non-forested gaps distribution, etc., could also be easily obtained for each stand. The capability to retain, if desired, the individual tree based information should be particularly useful to plan selective cuts or make some biodiversity assessments. This paper briefly describes the implementation of such an approach and shows preliminary results on the Nahmint experimental site.

TECHNIQUES AND METHODOLOGY

INDIVIDUAL TREE CROWN DELINEATION

In most mature coniferous forest or plantation, it is generally possible to isolate individual tree crowns and/or tree clusters using the bands of shade that typically separate them. These bands correspond to shaded ground or understory, or to shaded parts of the crowns. Using a smoothed (FAV⁺, see Figure 1) version of the near-infrared channel, which is typically better for general purpose inventory, the isolation process (ITCVFOL) first thresholds the image to remove large shaded areas. Assuming non-forested areas have been masked out (manually or by some pre-processing of the image), it then finds local minima in the remaining forested areas of the image. These minima correspond to the darkest pixels of shade between tree crowns. From these points, it systematically follows the valleys of shade which are found between the higher intensity crowns. This leads to a rather good initial separation of coniferous crowns, but for various reasons (e.g., a protuberant branch), most of them are not fully separated from their neighbours.

A delineation process (ITCISOL), which uses a rule-based approach to systematically follow from the inside a specific crown (or cluster) boundary in a clock-wise fashion, is utilized to produce more distinct crowns. From then on, the individual tree crowns are considered as distinct entities or objects, although for simplicity and compatibility with the image analysis system, the main output of the delineation process is a bitmap of ITCs. These automatic crown delineation techniques (ITCVFOL & ITCISOL), developed and tested using a 31 cm/pixel MEIS image (Gougeon, 1995b), were shown to lead to coniferous crown counts that were within 7.7% of those done on the ground. When errors of omission and commission were taken into account, 81% of the crowns were found to correspond one on one. With 60 cm/pixel casi images (Gougeon, 1998), the delineation is not as efficient, producing substantially more tree clusters. Research to find newer separation criteria and add more rules to the delineation process in order to improve the separation of tree clusters into ITCs is ongoing, although at this point in time, such separation may not be extremely critical to producing good inventory information.

INDIVIDUAL TREE CROWN CLASSIFICATION

Once the individual tree crowns (or clusters) are delineated, a crown-based supervised classification process is initiated (see Figure 1). Spectral signatures are acquired for representative tree crowns of each species and averaged to create the species signatures. For relatively uniform stands or plantations, this implies the delineation on the screen of sample areas for each species (using Imageworks⁺). The software (ITCSSG) then used the ITC bitmap produced by the delineation process to calculate the spectral signatures of the ITCs within the sample areas and amalgamate them to produce the species signatures. For mixed stands, specific ITCs can be picked up one by one to create the species signatures (using Imageworks⁺ and DCPE). This procedure is of course more demanding, although necessary, and has the added advantage of allowing the user to check whether he/she agrees with the automatic delineation. Indeed, by clicking on a tree crown in the image (under DCPE), the user is shown the crown that the system will use. ITCs for which the delineation does not appear appropriate can easily be rejected from amalgamation into the species signature by clicking on them again. This procedure should lead to rather pure species signatures, but it requires very precise ground information or a reliance on the user's interpretive capabilities. For these reasons, the first procedure is often used, as it was in this experiment, knowing that impurities are introduced into the species signatures. If not overwhelming in number or drastically different spectrally (e.g., hardwoods in a softwood stand), these impurities will typically slightly shift the means of species signatures and widen their distributions, making the classification process less precise.

After all of the ITC-based species signatures have been acquired, an ITC-based classification is run. For each ITC encountered in the image, its spectral signature is computed and compared with the various species signatures. A maximum likelihood decision rule is used to assign a species (class) to the unknown ITC. A confidence interval threshold is also used so that ITCs with signatures that are significantly different from any species signatures are left unclassified. Bitmaps showing all of the ITCs assigned to a given species (class) are

⁺ Denotes regular programmes from the PCI@environment.

produced and can easily be displayed. The existing classification system (ITCSSG and ITCSC) supports various ITC-based signatures (Gougeon, 1995a). Here, the multispectral average (and covariance matrix) of the crowns were used.

At the same time as training areas were delineated on the screen to generate the species signatures necessary for the classification, sample testing areas were also delineated to later test the classification accuracy (ITCCA). Similarly to the training process, these testing areas indicate sections of the image that are judged to be reasonably representative of a single species. They may, and generally do, contain impurities. Again, if detailed information had been available, specific testing ITCs could have been used instead of these more global testing areas. The ITCCA program compares one-on-one the classified ITCs with the ITCs contained in the testing areas and reports on the correctly and incorrectly classified crowns via a confusion matrix. Assuming that the test areas are pure, accuracy percentages are issued for each species, with an average species accuracy (assuming that all species are equally represented and important) and an overall classification accuracy (taking representation into consideration). More robust accuracy estimations are often achieved (as done here) by running two distinct classifications in which training and testing areas are interchanged. Classification results (Gougeon, 1995a, 1995c, 1996) with four or five coniferous species have usually been in the 72 to 81% range, depending on the spatial resolution used (30-100 m/pixel).

FOREST STANDS DELINEATION

Although information on an individual tree basis may be of interest to researchers with small pilot studies, or for sampling in an inventory context, or for very specific applications (e.g., selective cut), it is barely conceivable at this point in time to gather and keep this type of detailed information over large areas. Forest stands are still the preferred units of Canadian forest management inventories and even the newest vegetation and multi-resource inventories are based on static or dynamic regroupings. Of course, with the existing interfaces between image analysis and geographic information systems, it is easy to summarize the ITC-based information for existing stand boundaries (ITCPCD). This has the potential to produce detailed stand information on species composition, per species average crown areas, stand density and crown closure, average gap size and distribution, etc. However, for the assessment of new areas, an automatic regrouping of ITCs into forest stands or environmental strata is desirable. Fortunately, these regrouping are possible using image-wide quantification of parameters such as stem density, canopy closure, species concentrations, and others, followed by a simple pixel-based unsupervised classification, some filtering to eliminate areas not meeting minimum size criteria and to smooth out contours, and, a vectorization of the results.

A generic forest stand or environmental strata generation process is illustrated in Figure 2. Using the ITC bitmap produced by the delineation process (ITCISOL), a programme (CCLOSURE) creates an image where each pixel corresponds to the quantity of crown material found in a fixed-size roving window around that pixel. Similarly, another programme (STEMDENS) creates an image of stem density by reducing every crown to its center of gravity and summing the stems found in a fixed-size roving window. The same programmes are also used, once per species, on the species-specific bitmaps produced by the ITC classification. Then, all of the images produced are input to a pixel-based unsupervised classifier. The classification is repeated a few times, asking for a different number of classes, until a regrouping judged reasonable is achieved. When satisfied, stands smaller than a given minimum area are removed (SIEVE⁺), and a mode-based filtering (FMO⁺) is done to smooth out the stand boundaries. Finally, the classes are fed to a raster to vector conversion programme (RTV⁺) in order to obtain polygons that can be transferred to a geographic information system (GIS). The ITC-based information within the newly generated boundaries can be extracted (ITCPCD) and also ported to the GIS as polygon attributes. For this experiment, it was found that the stem density information was sufficient to produce the stand boundaries.

IMAGERY, STUDY SITE AND FIELD DATA

The Compact Airborne Spectrographic Imager (casi) is a Canadian-made pushbroom sensor capable of acquiring multispectral imagery in the visible to near-infrared part of the spectrum (Anger *et al.*, 1994). Originally built as a sampling spectrometer, it now offers various modes in which trade-offs are made between the spectral and spatial resolutions. For this study, eight spectral bands (~25nm) were acquired over an area

known as the "Nahmint species trial site". Flown at an altitude of 500m, its 512 across-track pixels with a 38° field of view led to a spatial resolution of 60 cm/pixel. This data is a subset of a much larger dataset acquired over various areas of Vancouver Island, British Columbia, by Itres Research, in collaboration with MacMillan Bloedel Ltd. and the Pacific Forestry Centre, as part of a 3-year joint project aimed at producing certifiable techniques of forest assessments using high spatial resolution multispectral imagery.

The Nahmint site is located by the Nahmint River, south of Port Alberni. It was established to compare height and volume growth of five coastal coniferous species (Dunsworth, 1990): Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), amabilis fir (*Abies amabilis*), western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*). The trees are still very young, having been planted in 1979/80 following logging of the area in 1977/78. Some natural regeneration also took place. Figure 3 shows a geometrically corrected pseudo-colour infrared rendition of the casi image acquired over the Nahmint site. Delineated areas represent specific species that were used to alternatively train and test the classifier. A class of hardwood, composed mostly of alder (*Alnus rubra*) was added for completeness. More information about the existing species composition of the stands was later acquired by gathering data in the field for areas spanning two metres on each side of transect lines. The image channels were also corrected to compensate for the bi-directional effects of the sun and view angles on the trees' spectral signatures using a simple column histogram equalization procedure (Yuan & Leckie, 1992).

RESULTS AND DISCUSSION

Following the methodology depicted in Figure 1, the near infrared channel of the casi image was smoothed with a 3x3 kernel (FAV*), individual tree crowns (or tree clusters) were extracted (ITCVFOL & ITCISOL), species signatures were generated (ITCSSG) and a supervised classification was performed (ITCSC) and tested for accuracy (ITCCA). For these preliminary results, the multispectral mean of the crowns were used to generate the species signatures and classify the individual tree crowns. Because field-based information on an individual tree basis was not available, the six species signatures were obtained by manually delineating areas known to be relatively pure (see Figure 3). The signatures of all ITCs in a given area are averaged to create the species ITC-based signature. The classification process compared the signatures of all ITC's in the image with the six species signatures and attributed classes using a maximum likelihood decision rule. The results of the ITC-based classification process are shown in Figure 4. Classification accuracy was assessed on an ITC basis using distinct testing areas, also assumed relatively pure. The confusion matrix shown in Table 1 is an amalgamation of the two classifications obtained by interchanging the testing and training areas. This is a more robust estimation.

An overall classification accuracy of 59.8%, derived from one classification at 53.1% and the other (with training-testing areas reversal) at 68.2%, was obtained (see Table 1). The western hemlocks were easily separated (83.0%) from other species, with minor confusion (11.3%) with Douglas fir. The hardwoods were also well recognized (68.1%), with some confusion with western hemlocks (12.5%) and western redcedars (18.1%), but no confusion at all with the other conifers. The two types of "real" firs are relatively well recognized (59.0%, 57.5%), with confusion mostly among themselves, and a potential accuracy for fir as a single combined class of the order of 80%. The Douglas firs (*Pseudotsuga menziesii*) are also relatively well recognized (63.9%), with almost equal minor confusion with the two types of "real" firs (9.3% & 11.1%) and the hemlocks (13.9%), and practically no confusion with the cedars (1.9%). The poorest classification accuracy is obtained with the western redcedars (27.4%), which are significantly confused with the Douglas firs (34.3%) and the amabilis firs (26.5%). This is surprising because the cedars are visibly distinct in the original near-infrared rendition of our image. However, spectrally, the cedars are located in between these two species and both their signatures have broader spreads. Thus, the maximum likelihood criteria being used will tend to favour the firs.

Although the classification looks very good (Figure 4), the classification accuracies, as depicted by the confusion matrix, are rather low. This is can be attributed to the lack of purity of the training and testing areas, mostly due to in-filling of the stands since their original plantation. This degrades the classification in two ways: a) it makes the means of spectral ITC signatures assigned to given species imprecise and creates signatures with broader intra-species variations than expected; b) it brings an a priori confusion to the testing

process which is based on the premise that the testing areas are pure. In fact, if in-filling of stands was known to be a uniform 10% or 15%, then classification accuracy figures could essentially be augmented by the same proportions. Alternatively, better classifications and better classification accuracy reports (ITCCA) could be achieved by removing the undesirable trees from both the training and testing areas. This could be accomplished by relying on the user to interpret the image and select the specific ITCs to train and test the classifier or, more efficiently, still use the area-based training and testing, but remove one by one the undesirable trees. Another possible approach relies on iterative classifications to improve accuracy. These various alternatives are being explored.

The individual tree crowns were regrouped into forest stands using the semi-automatic methodology described earlier and depicted in Figure 2. The resulting stand delineation appears very convincing (see Figure 4). Of course, whether using the automatically delineated stands or existing historical forest inventory stands, with the successful use of such approaches, the species contents of such stands could be known with a level of details never achieved before. Information such as average crown area, average tree distances, non-forested gap sizes, canopy closure, stem density, etc., and parameters about their spatial distributions, can also be calculated for each stand, and if desired, for each species within a stand. Similarly, this type of information can be also be accumulated for wider areas.

Another systematic evaluation of the ITC-based classification results was carried out by comparing the species content of larger test areas with field-based transects through these stands. The approximate location of the transects and their corresponding test areas are shown in Figure 5. The transects consisted in following a compass bearing and noting the characteristics of trees within two meter on each side of the transect lines. Information such as species, dominance, potential aerial visibility, approximate crown size, distance along the transect line, etc., were recorded for each tree. These transects provide more accurate descriptions of the situation on the ground. In addition, they are a well recognized forestry tool. Table 2 shows the differences between the species content of our larger test areas as summarized from the ITC classification and that gathered by the transects when disregarding the small trees judged not visible from the air. On average, the dominant species is off by 19.5%, and the error, when all species are considered equal, is 12%. The average error by site is also of the same order (11.5%). However, for any given site, significant differences are possible. For example, for site J the dominant species is off by 38%.

An ultimate evaluation of the ITC-based classification results would be done on a tree by tree basis. However, even with the availability of today's sophisticated GPS positioning on the ground and the rather precise geometric corrections of aerial images, such an evaluation is still not practical because of the high crown closure and stem density of these stands. None of the test procedures used assess whether the tree crowns were well delineated or even well separated. It is also worth noting that because the image was radiometrically normalized for view and sun angles, which as revealed by other studies on high resolution aerial images (Leckie *et al.*, 1995) can be an important factor in purely multispectral species recognition, off-nadir crowns to the right of the image tend to be classified better than in a previous study that did not use BRDF corrections (Gougeon, 1997).

CONCLUSION

A 60 cm/pixel *cas* image of forest plantations on Vancouver Island, Canada, was analyzed using a system for delineating individual tree crowns, identifying their species and regrouping them into forest stands. When tested with a conventional confusion matrix approach, the ITC-based supervised classification of five western Canadian coniferous species and a generic hardwood class, led to an overall classification accuracy around 60%. The difficulties in separating some species, mostly western red cedar, are attributed to very close species spectral signature means and broad intra-species variations. The low classification results observed with the confusion matrix approach are also attributed to the lack of purity of the training and testing areas. A comparison of the results with field transects led to an overall error of 12%, 19.5% if only the dominant species is considered. However, the issue of whether the tree crowns were well delineated (for crown area), or even well separated (for stem counts), was not addressed at this time. The radiometric normalization of the image for view and sun angles improved the purely multispectral species recognition of the most off-nadir trees (relative

to previous work (Gougeon, 1997)). The semi-automatic forest stand delineation methodology produced stand outlines very similar to the existing ones.

The present body of work indicates that similar and even better results are achievable with a variety of 30-100 cm/pixel multispectral images. Consequently, good possibilities are expected with images from the next generation (Fritz, 1996) of earth observation satellites (82-100 cm/pixel). The possibility of obtaining from digital remote sensing the kind of information that foresters need in order to manage the forest resource may be within reach. An ITC-based paradigm also facilitates the assessment of newer inventory parameters such as non-forested gap distributions, snag locations, and other biodiversity and wildlife criteria and indicators needed for the multipurpose management of our forests.

These encouraging conclusions should be tempered by the fact that there are still several research and operational problems to resolve before the goal of semi-automatic generation of precise forest management inventories is achieved. To address these concerns, research is ongoing with issues such as: deciduous tree crown delineation, crown-based texture and structure signatures, height, merchantable wood volume and biomass estimations, unsupervised classification, radiometric corrections and signature extension, view and sun angle effects, topography, etc. A different type of system may be needed to take all of these factors into account. Figure 6 shows a system where decisions to identify the species of an individual tree crown are made in an incremental fashion by accumulating, as needed, evidences from the spectral, textural, structural and spatial realms. Such a rule-based species recognition system is more akin to the human photointerpretation thought process.

ACKNOWLEDGMENTS

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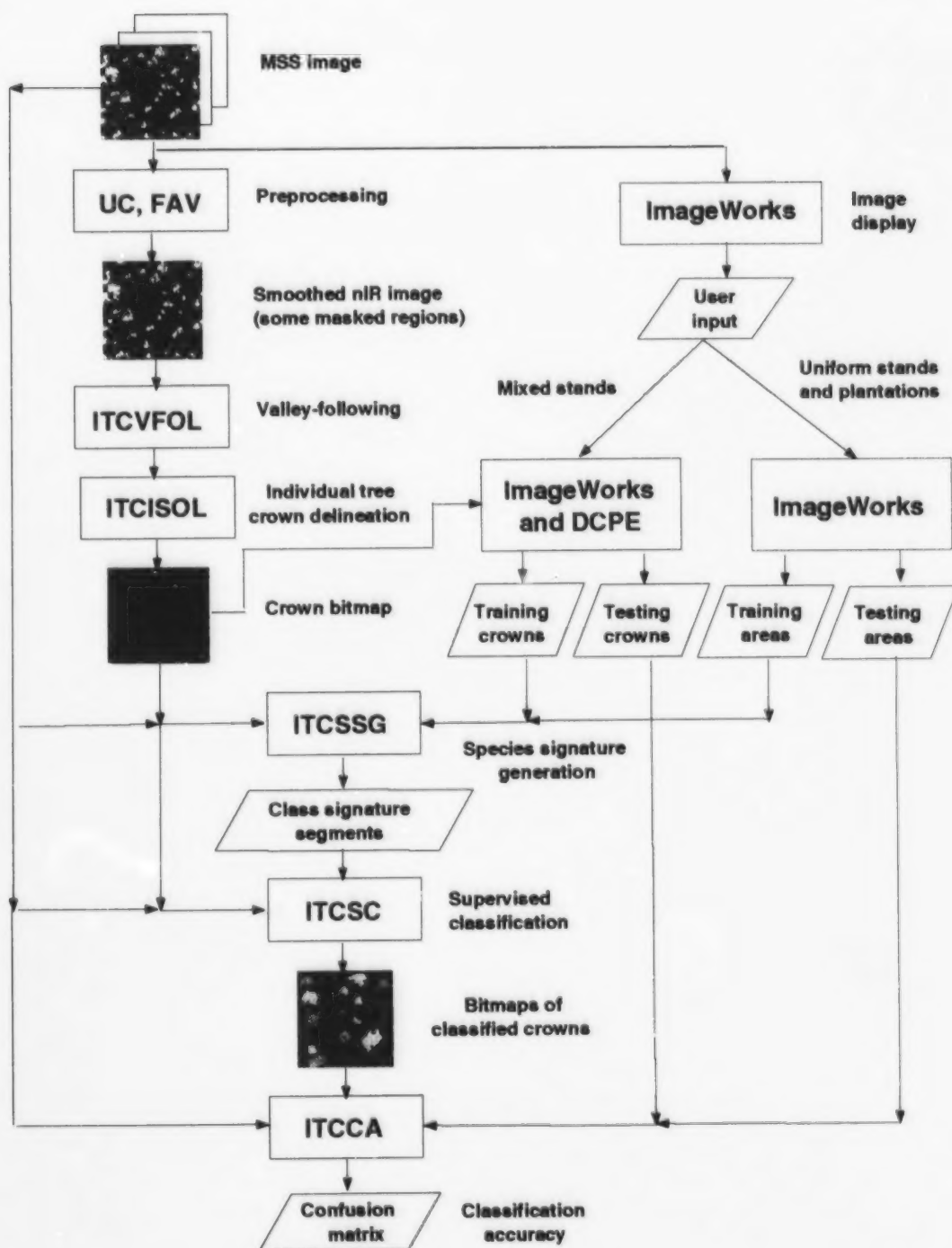


Figure 1. Methodology for individual tree crown delineation and supervised classification from high spatial resolution multispectral images (from Gougeon, 1997).



Figure 3. Pseudo-colour infrared rendition of a sub-area of a geometrically and radiometrically corrected Casi image (60 cm/pixel) of the Nahmint Lake species trial area in the central forest of Vancouver Island, British Columbia, Canada. The training and testing areas used for the classification were delineated where species are known to be almost homogeneous (Dunsworth, 1990). Their respective species and colours are: Douglas-fir (*Pseudotsuga menziesii*) in red, grand fir (*Abies grandis*) in green, amabilis fir (*Abies amabilis*) in blue, western redcedar (*Thuja plicata*) in orange, western hemlock (*Tsuga heterophylla*) in yellow, and hardwoods in light blue.

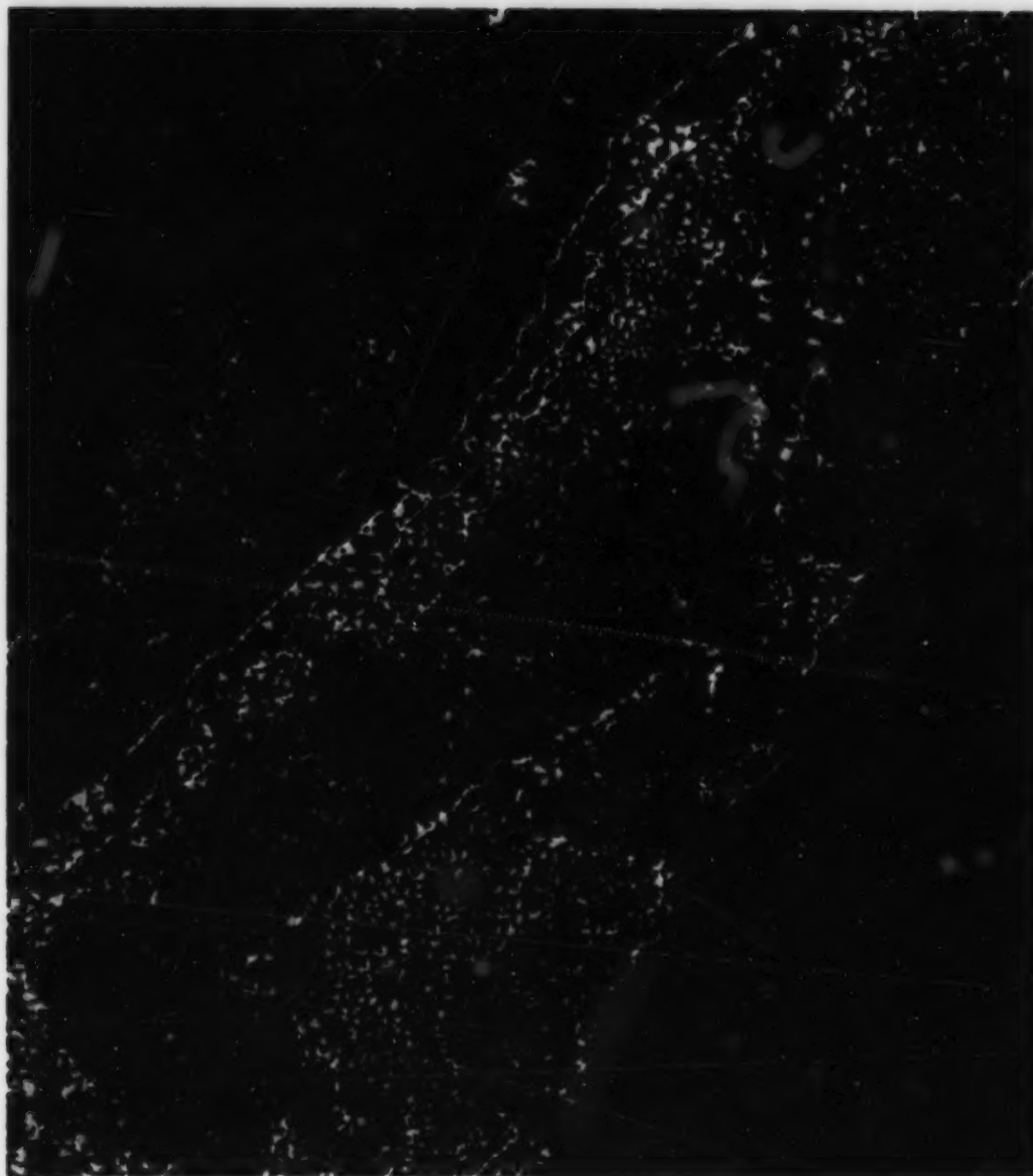


Figure 4. The individual tree crown (ITC) classification of Figure 3 and its computer generated forest stand outlines using the same colour scheme as Figure 3.

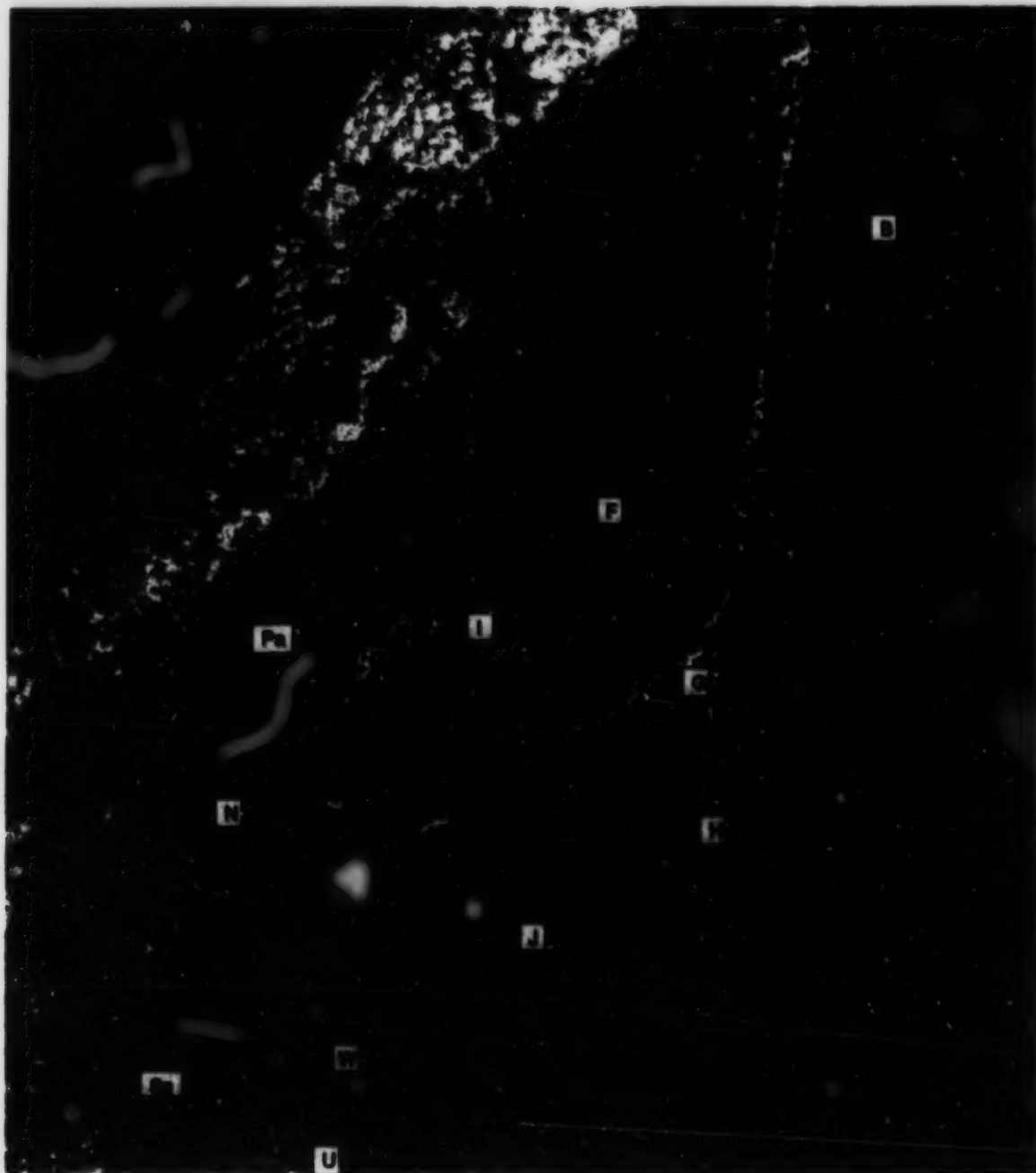


Figure 5. Sample sections of forest stands and ground transect locations used in producing the species composition comparisons of Table 2. The species colour scheme is the same as in Figure 3.

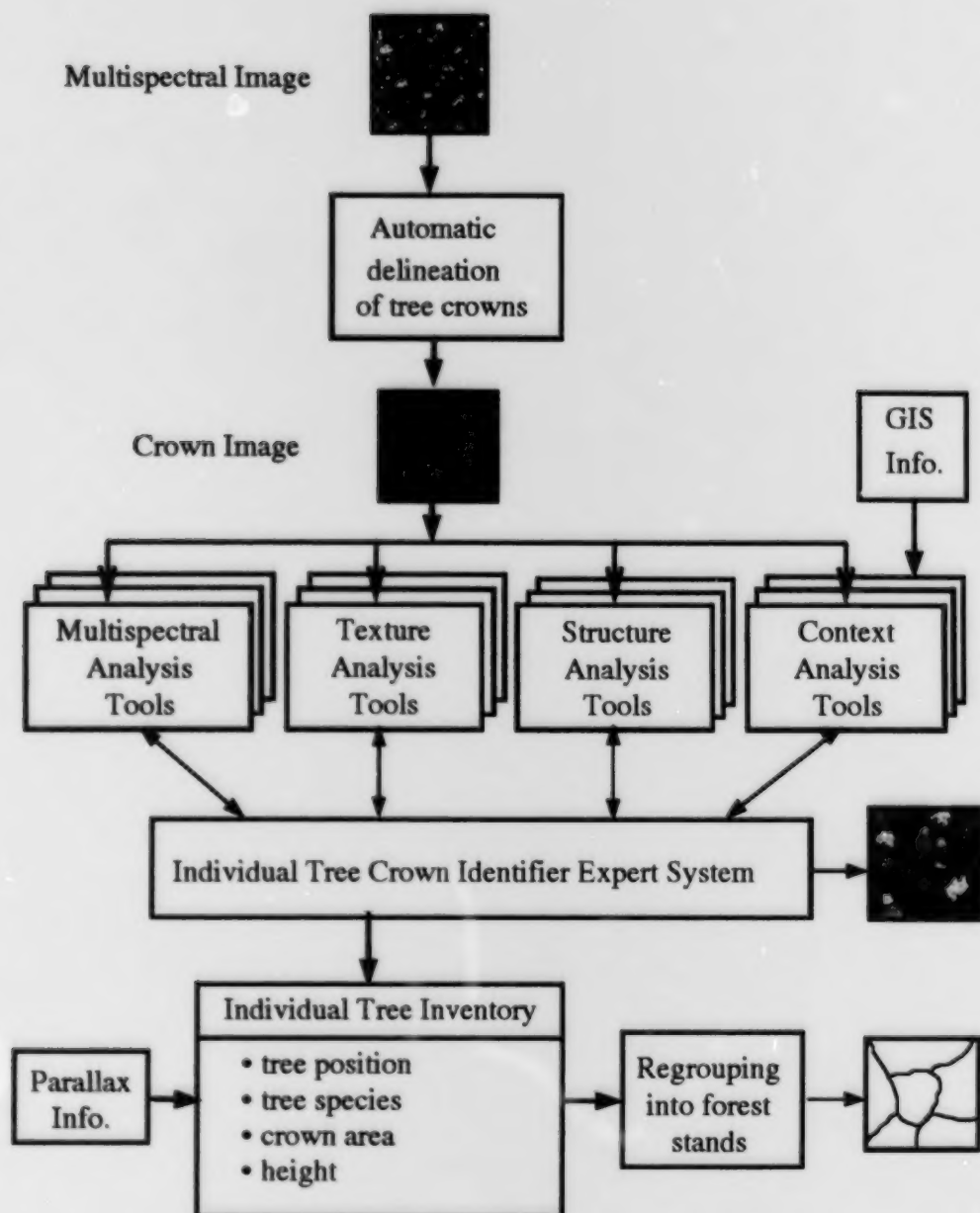


Figure 6. Proposed knowledge-based system making species decisions on an individual tree basis by accumulating evidences from different domains in order to produce a forest inventory from high spatial resolution multispectral images (30 - 100 cm/pixel).

MODELING OF TREE SPECIES AND STRUCTURAL ATTRIBUTES FROM HIGH RESOLUTION MULTI-SPECTRAL IMAGERY USING DECISION TREE ANALYSIS FOR EAST COAST EUCALYPT FORESTS OF AUSTRALIA

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ABSTRACT

Tree clusters formed from 2m resolution multi-spectral imagery using the University of Melbourne TIDA algorithm have been classified using decision tree analysis to produce models which predict the distribution of tree species, stem diameter, tree height, and an index of tree physiological age. Data from field sites at Batemans Bay, on the south coast of New South Wales, Australia, has been applied to map a range of forest types from rainforest to tall moist old growth forest and dry open forest. The method uses image spectral and spatial attributes as well as terrain and climate attributes. The reliability of these models is compared against the reliability of forest type and structure maps produced by interpretation of 1:25,000 colour aerial photographs.

Keywords: forest structure mapping, tree species mapping, Digital Multi-Spectral Video, DMSV, decision making trees, aerial photo interpretation.

RÉSUMÉ

MODÉLISATION, PAR ANALYSE ARBORESCENTE DE DÉCISION, DES ESPÈCES D'ARBRE ET DES ATTRIBUTS STRUCTURELS DES FORÊTS D'EUCALYPTUS DE LA CÔTE EST AUSTRALIENNE À PARTIR D'UNE IMAGERIE MULTISPECTRALE À HAUTE RÉOLUTION

Des regroupements d'arbres réalisés à partir d'une imagerie multispectrale prise à une résolution de 2 m et à laquelle on a appliqué l'algorithme TIDA de l'Université de Melbourne, ont fait l'objet d'une classification à l'aide de l'analyse arborescente de décision en vue de produire des modèles prédictifs de la répartition des espèces, des diamètres de tiges et des hauteurs d'arbres ainsi qu'un indice de l'âge physiologique des arbres. On s'est servi des données portant sur 21 sites dans la région de Batemans Bay, sur la côte sud de la Nouvelle-Galles du Sud, pour cartographier divers types de forêts, notamment les forêts ombrophiles, les vieux peuplements humides composés d'arbres de haute taille et les forêts sèches claires peu denses. La méthode repose sur l'analyse des données spectrales et spatiales et des attributs de relief et de climat fournis par ces

images. La fiabilité des modèles est comparée à celle de la cartographie des types et structures de forêts issue de l'interprétation de photos couleur aériennes produites à l'échelle de 1/25 000.

INTRODUCTION

CONTEXT

Forest management agencies in Australia have a need to demonstrate that harvesting of native *Eucalyptus* forests is being conducted in a manner which is ecologically and economically sustainable and without compromising the forest's social value. This requires assessment of critical 'base line' forest attributes and monitoring of forest changes at local, regional, and national scales.

Current assessment techniques are based primarily on a relatively low intensity of field samples and mapping by interpretation of 1:25,000 scale colour aerial photographs. The capacity of these techniques is being pushed to meet rising demands for high reliability estimates, particularly for monitoring purposes. The difficulty in achieving reliable quantitative relationships between field measurements and maps from 1:25,000 photography is well known, but forest management agencies have limited options. Forest agencies are also under substantial time pressures to complete regional forest assessments in all major forest regions of Australia to define a new comprehensive network of conservation reserves.

Interpretation of larger scale aerial photographs would produce more reliable maps, but their use has been largely abandoned because of the time and cost involved in mapping large areas. Within Australia there have been a number of studies utilizing satellite remote sensing including Landsat TM, Landsat MSS, and NOAA to monitor changes in broad forest structural classes, however the results have been of little benefit to forest managers who are principally concerned with tree structural and floristic attributes at landscape or finer scales. The failure of satellite based remote sensing within Australian forestry has been attributed to a number of factors including the high degree of speciation of the genus *Eucalyptus*, the mountainous terrain which is typical of much of Australian forests, as well as over-promotion of satellite remote sensing technologies. As a result, most experience to date has been in base line assessment of basic floristic and structural attributes, including attributes important to delineate old growth forest. This experience may not be applicable to the more challenging problem of change detection for monitoring purposes.

Forest management agencies in Australia appreciate that there is a dire need for a fresh approach toward forest monitoring which can meet local, regional, and national reporting needs. There is a growing appreciation that automated or semi-automated analysis of new high resolution imagery may provide part of a solution to the current dilemma.

OBJECTIVES

Background

State Forests of New South Wales (NSW) initiated a Spatial Integration Project in mid-1996 to review the capacity of high resolution digital remote sensing to provide a mechanism for improved forest assessment and monitoring. The project was conceived after inspecting four band 2m Digital Multi-Spectral Video (DMSV) imagery obtained for the CSIRO Multi-Divisional Program on Forest Productivity at Batemans Bay on the South Coast of Australia, about 400km from Sydney. The potential of this type of imagery was apparent because differences in forest species and structure was readily discernible from viewing of the imagery.

It was anticipated that information from DMSV imagery, which is collected in frames like aerial photographs, could be readily correlated to a map base using aerial triangulation techniques. Environmental data sets were also to be included in the spatial integration project because of a body of experience that spatial attributes describing the physical environment (ie., climate, regolith, topography) can markedly improve the reliability of maps produced using remote sensing imagery. Field surveys also formed an integral part of the project.

Analysis presented here builds on earlier work reported by Preston (1997) which provided an initial report of findings from the Spatial Integration Project. Since that time, additional field data and new imagery has been obtained, allowing expanded analysis. This earlier report also used data obtained from multi-stage sampling using 1:5,000 colour aerial photographs. Exploration of multi-stage sampling has been since abandoned because of inadequate reliability of species identification from aerial photos.

Objectives

The study sought to evaluate techniques for a new approach to forest assessment and monitoring which would address known deficiencies with the current procedures involving aerial photo interpretation, stratification, and field survey. The project would seek to evaluate the feasibility of developing an integrated approach to forest assessment which would evaluate:

- The use of a single spatial unit based on a combination of forest composition and structure,
- The use of forest structure and species maps as the basis for more detailed assessment of wood volumes and productivity, fauna habitat, and historical disturbance,
- The use of quantitative procedures to ensure explicit relationships between field data and map data can be consistently and reliably applied,
- The integration of field surveys to fully exploit information from GIS and remote sensing.

STUDY AREA

The study area is 70km north west of Batemans Bay and 400km south of Sydney. The area is shown in Figure 1. The elevation of the study area ranges from about 170m to 520 m. The major overstorey tree species in the study area is silvertop ash (*Eucalyptus sieberi*). Other open-forest species include yellow stringybark (*E. muelleriana*) and rough-barked apple (*Angophora floribunda*). The major tall-forest species are mountain grey gum (*E. cypellocarpa*), brown barrel (*E. fastigata*) and large-fruited red mahogany (*E. scias*). The vegetation of the South Coast region is described in more detail by Austin, et al. (1995) and Doherty and Coops (1995). The tenure of the study area includes State Forest, National Park and freehold.

METHODS

DATA COLLECTION

Field data

Standard plot assessment procedures were initially used to measure trees in circular plots. A total of 17 field plots were subjectively located within five manually delineated sampling strata. Attributes were recorded for all trees over 10cm dbh within a 10m radius of the plot centre. Attributes were also recorded for up to 4 remnant trees occurring up to 50 m from the centre of the field plot if they were taller than trees in the 10 m plot.

Table 1. Tree attributes recorded at field plots.

Tree no.
Species
dbh (cm)
Canopy stratum (Emergent, Tallest, Mid)
Canopy position (Dominant, co-dominant, sub-dominant, overtopped)
Tree height
Tree development index (1-20) (an ordinal indicator of physiological maturity)
Is tree within 10 m or 50 m radius of plot centre

Large scale stereo photography at 1:5,000 scale was acquired for the study area to assist with visual correlation of tree location on the ground with their location on the aerial photos. Their locations marked on

1:5,000 photos was then transferred to DMSV imagery. This proved difficult due to different camera and sun orientation between the two sets of imagery and the relatively lower resolution of the DMSV imagery. As a result, not all trees were able to be used in modeling. Of 279 trees measured at the 17 plots, 224 trees were able to be spatially associated with DMSV imagery.

Aerial digital imagery

DMSV imagery was acquired in October 1996 by an Australian company, SpecTerra Systems, using four digital video cameras on board a Cessna 182. Cameras are mounted in a special housing along with an industrial computer system. Each camera is fitted with a specialized filter so that it collects only one spectral band. These are, respectively, blue (440–460 nm), green (540–560 nm), red (640–660 nm), and near infrared (740–760 nm). Data were obtained at 2 m spatial resolution, which was subsequently resampled to a 1 m resolution during the rectification process. Each video frame measures 540 × 720 pixels. Data was pre-processed to co-register each of the four bands, minimise bi-directional reflectance and any hotspot effect by SpecTerra Systems and mosaicked using tie-points to join frames and control points selected from triangulated 1:15,000 photography.

GIS data

A number of spatial environmental attributes were calculated using contour and streamline data from 1:25,000 topographic maps. ANUDEM software (from the ANU Center for Resource and Environmental Studies) was used to produce a hydrologically sound DEM which was then analyzed to produce secondary terrain attributes such as annual net incident solar radiation (NETRAD) and compound topographic index (CTI) which indicates position on slope. Elevation, NETRAD and CTI attributes have found to be significantly correlated with properties affecting soil profile development, water balance, and temperature as these environmental attributes affect plant distribution and development (P.Ryan; N. Coops, pers. comm.). Figure 2 shows these surfaces for the study area.

Aerial photo interpretation

A forest type and structure map was produced for the area using conventional NSW mapping techniques by an experienced botanist and aerial photographic interpreter who was familiar with the study area using colour 1:25,000 aerial photographs flown in 1991. Forest type classification was based on the standard SFNSW Baur system (Anon, 1989) and structural mapping was conducted in accordance with standards currently being used for the comprehensive regional assessment project in NSW (R. Squire, pers. comm). Forest types and structural attributes were described for different forest units (ie., they do not use the same base polygons). All line work was manually transferred to a 1:25,000 hard copy of DMSV imagery prior to digitizing. Details of attributes are given in Table 3. Figure 3 shows the nature of polygons used for forest type mapping drawn from aerial photographs and compares them against the DMSV image mosaic.

IMAGE ANALYSIS

Evaluation of existing classification techniques

Initially, traditional per-pixel unsupervised and supervised algorithms were tested to classify DMSV imagery, but results were disappointing. Tree crowns were made up of several different classes, and there was considerable overlap with trees of different species and with non-forest land cover types. Some evaluation of more advanced image segmentation techniques (intended for use with Landsat imagery) was also conducted. These tools did not define spatially or spectrally meaningful image objects which coincided with tree crowns or parts of tree crowns. It was concluded that a more intelligent algorithm was required which was more suited for forest specific segmentation of high resolution DMSV imagery.

Image segmentation

A Tree Identification and Delineation Algorithm (TIDA) was developed (Culvenor et. al, 1998) in parallel with the Spatial Integration Project to process the DMSV imagery. TIDA searches for distinct spectral patterns

in a forest scene and use specific image features for the automated delineation of tree crowns. These include the spectral maxima and minima, being indicative of crown centroids and boundaries respectively.

Initial testing of the algorithm in combination with field verification indicated that TIDA often identified small patches of forest canopy which 'looked' like a single tree crown rather than individual canopies. This is due to the tendency of eucalypt tree crowns to bunch together and the relatively coarse resolution of the DMSV imagery. As a result, the term "tree cluster" was coined to describe these canopy objects, with an understanding that clusters may contain groups of trees of different species and trees with different structural attributes. Figure 4 shows examples of tree clusters at the Batemans Bay study area.

Calibration of TIDA involved sensitivity analysis on a number of key input parameters with the aim of determining a balance between the need to identify individual clusters versus avoiding fragmentation of larger or single tree clusters. The implemented version of the software was successfully applied to produce about 89,000 clusters for this study area of about 900ha (ie., about 100 clusters per ha). Clusters are typically about 6-10m in diameter may occur as large as 20m diameter. The smallest clusters are 2m in diameter by definition. Figure 5 shows an example of image clusters for part of the study area.

It is recognized there is considerable opportunity for improvement of the algorithm, however, it provides a useful image analysis tool that overcomes difficulties with per-pixel classification of high resolution imagery.

SUMMARY OF FIELD AND SPATIAL DATA

Identification of the individual plots on the aerial photography allowed measured trees to be collapsed into clusters as defined by the TIDA algorithm. In total 224 trees across 17 plots were collapsed into 98 tree clusters. About half of the clusters consist of one tree and more than 90% of clusters are made up of four or less trees. Seventeen different tree species were recorded in the field data, but only five species (where all rainforest species are grouped as one species) were recorded as being dominant at seven or more clusters. For this reason, only distributions of these moderately common species were modeled: *E. sieberi*, *E. fastigata*, Rainforest species, *E. muelleriana*, and *E. scias*.

Four groups of variables (species, size and density, development and height) were calculated so as to provide a useful range of explicit structural and compositional attributes needed for ecological and economic management of forests. For species attributes, both categorical and continuous attributes were calculated to appraise the benefits of different modeling strategies. Attribute calculated for each cluster are listed in Table 2.

Table 2. Dependant variables calculated from individual tree attributes measured during field surveys.

Dependant variable	Name	Explanation / comments
<i>a. Species</i>		
Dspecies	Dominant species name	Name of overstorey tree species which as highest BA percent in a cluster
Sieb	<i>E. sieberi</i> percent	Percentage BA >10cm dbh in cluster which is <i>E. sieberi</i>
Rain	Rainforest species percent	Percentage BA >10cm dbh in cluster which are rainforest tree species
Fast	<i>E. fastigata</i>	Percentage BA >10cm dbh in cluster which is <i>E. fastigata</i>
Scia	<i>E. scias</i>	Percentage BA >10cm dbh in cluster which is <i>E. scias</i>
Muel	<i>E. muelleriana</i>	Percentage BA >10cm dbh in cluster which is <i>E. muelleriana</i>
<i>b. Size and density</i>		
dbh1	Basal area 10-30 dbh	Basal area (sq cm) of all trees in a cluster from 10-20 cm dbh
dbh2	Basal area 30-50 dbh	Basal area (sq cm) of all trees in a cluster from 30-50 cm dbh
dbh3	Basal area 50-90 dbh	Basal area (sq cm) of all trees in a cluster from 50-90 cm dbh
dbh4	Basal area 90+ dbh	Basal area (sq cm) of all trees in a cluster from 90+ cm dbh
Batot	Basal area 10+ dbh	Basal area (sq cm) of all trees in a cluster over 10 cm dbh
<i>c. Tree development index</i>		
tdi1	TDI percent sapling / young	Percentage BA >10cm dbh in cluster with TDI 1-5
tdi2	TDI percent early / mature	Percentage BA >10cm dbh in cluster with TDI 6-9

<i>Dependant variable</i>	<i>Name</i>	<i>Explanation / comments</i>
tdi3	TDI percent late mature	Percentage BA >10cm dbh in cluster with TDI 10-13
tdi4	TDI percent stag	Percentage BA >10cm dbh in cluster with TDI 14-19
<i>d. Height</i>		
Maxht	Maximum height	Height of tallest tree in a cluster
h1	Height percent 10-20m	Percentage BA >10cm dbh with height 10-20m
h2	Height percent 20-30	Percentage BA >10cm dbh with height 20-30m
h3	Height percent 30-40m	Percentage BA >10cm dbh with height 30-40m
h4	Height percent 40+	Percentage BA >10cm dbh with height 40m +

Independent variables

A suite of independent variables was calculated from DMSV imagery based on the median attributes of the four bands. Median values were used instead of the average because of simple software limitations. The median may approximate the mean value of clusters with a normal distribution, but this was not able to be assessed in this project.

Table 3. Independent (spatial) variables produced for the study area from interpretation of 1:25,000 aerial photographs, DMSV imagery, and terrain modeling.

<i>Independent variable</i>	<i>Name</i>	<i>Explanation / comments</i>
<i>Variables produced from interpretation of 1:25,000 aerial photos</i>		
api_dens	Crown cover percent	Relative density of the overstorey canopy. 1=0-25%, 2=25-50%, 3=50-75%, 4=75-100%
api_dist	Disturbance indicator	Where indicators of human disturbances can be clearly seen For example 4=high incidence of uneven tree heights.
api_fors	Overstorey species type	Baur forest type (see Anon, 1989) 12 = Coachwood Sassafras, 112 = Silvertop Ash, 114 = Silvertop Ash - Stringybark, 155 = Brown Barrel, 157 = Yellow Stringybark-Gum, 165=Gully Peppermint
api_mat	Mature growth stage	Relative proportion of forest unit which is in the mature growth stage. 0=<30%, 1=30-50%, 2=50-70%, 3=>70%
api_rain	Rainforest	Rainforest / eucalypt forest binary map
api_reg	Regrowth growth stage	Relative proportion of forest unit which is in the regrowth growth stage. 1=<10%, 2=10-30%, 3=30-50%, 4=50-70%, 5=>70%
api_sen	Senescence growth stage	Relative proportion of forest unit which is in the senescing growth stages. 1=>30%, 2=10-30%, 3=<10%
api_site	Site height	Maximum height that trees would attain at that site. 0=<20m, 1=20-40m, 2=>40m
api_size	Size of regrowth	Approximate size of the regrowth growth stage 1=10-30cm dbh, 2=30-50cm dbh, 3=10-50cm, 4=regrowth < 10%
<i>Independent variables from DMSV imagery</i>		
clu_area	Area of cluster	Area (sq. m) of cluster formed from DMSV imagery
clu_b1med	DMSV Band 1	Median value in band 1 of pixels in DMSV cluster
clu_b2med	DMSV Band 2	Median value in band 2 of pixels in DMSV cluster
clu_b3med	DMSV Band 3	Median value in band 3 of pixels in DMSV cluster
clu_b4med	DMSV Band 4	Median value in band 4 of pixels in DMSV cluster
clu_b2on1	DMSV ratio of Band 2 on 1	Median value in band 2 of pixels in DMSV cluster divided by median value in band 1 of pixels in DMSV cluster

<i>Independent variable</i>	<i>Name</i>	<i>Explanation / comments</i>
clu_b2on3	DMSV ratio of Band 2 on 3	Median value in band 2 of pixels in DMSV cluster divided by median value in band 3 of pixels in DMSV cluster
clu_b4on2	DMSV ratio of Band 4 on 2	Median value in band 4 of pixels in DMSV cluster divided by median value in band 2 of pixels in DMSV cluster
clu_b4on3	DMSV ratio of Band 4 on 3	Median value in band 4 of pixels in DMSV cluster divided by median value in band 3 of pixels in DMSV cluster
<i>Independent environmental variables</i>		
env_cti	CTI	Compound topographic index from 25m DEM indicates position on slope
env_elev	Elevation	Elevation above sea level using 25m DEM from 1:25,000 topo maps
env_netrad	Net radiation	Net solar radiation indicates aspect / slope effect

DECISION TREE MODELING

Model development

Decision Trees provide a method of establishing a set of statistically significant rules which define the relationship between a dependant variable (ie., a field variable) and a number of independent variables (ie. remotely sensed data and environmental attributes). Decision Trees have been used in a number of instances in the analysis of remotely sensed data and environmental data (e.g., Lees and Ritman, 1991). The concept is similar to the more widely applied linear regression. One of the main differences between linear regression and decision tree analysis is that it can readily manage both categorical and continuous attributes as both dependent and independent variables (see de Ville, 1990). The Knowledge Seeker package (version 3.10.01) from Angoss Software, was used in this analysis. It is preferred to other implementations of decision trees because trees can be readily amended based on expert knowledge. One of the main useful results of decision tree modeling is a set of Boolean rules (based on the model) which can then be applied to the full spatial dataset to predict the distribution of attributes for the unsampled portion of the population.

The reliability of each model is described using the percentage of variance explained (PVE), which is analogous to the more familiar R-squared term from linear regression. The PVE value reported in this study is based on the iterative re-substitution of a learning data set through the model and is known to overestimate the model reliability compared to use of an independent data set. It is incorrect to interpret this figure as an accuracy estimate, which should be determined from an independent data set.

Two sets of models were developed. The first stage involved the development of decision trees which used the most statistically significant combination of independent variables. These 'statistical' models were then adapted to produce a second set of models where the independent variables, which were statistically valid, were subjectively chosen based on the known environmental requirements of the modeled cluster attributes. As a result, this second set of models are known as "quantitative expert models". While the combination of independent variables in these 'expert' models may explain less of the overall variance than the 'statistical' model, they are generally considered more ecologically rigorous as they allow local knowledge such as 'the tallest trees are *E.fastigata*' or 'Rainforest does has very few or nil over-mature trees' to be readily included into the analysis. Likewise, preference was given when developing 'expert' rules to ratios of DMSV bands rather than individual bands as the 'ratioed' value is less susceptible to brightness variations introduced through mosaicing and terrain effects. Finally, preference was given to compound topographic index and net radiation rather than elevation, as plant distributions were considered to be more related to the former two variables than a direct response with elevation.

Due to the exploratory nature of these analysis, a broad confidence level of 90% (0.1) was set as the minimum significance for any split of any independent variable developed using DMSV data sets. The significance level was relaxed for development of rules from aerial photo interpretation data sets, where a minimum confidence level of 80% was used. A confidence level of 80% was also accepted for a small number

of splits in the DMSV models where the choice of these independent variables was found to significantly improve the reliability of the model. An example of a decision tree is given in Figure 6.

The same field data set was used to calculate field dependant variables, based on clusters, that were applied for both DMSV models and API models. This approach favours the DMSV models, but is more suitable for the purpose of model development than alternative approaches such as calculating plot means.

Implementation of predictive models

A variety of decision rules were produced as shown in Figure 7 which describe a series of Boolean rules showing the relationship between field attributes and spatial data at field sites. These rules were reformatted and loaded into the GIS system to predict attributes for all clusters in the study area.

RESULTS & DISCUSSION

MODELS FROM DMSV IMAGERY AND PHYSICAL ENVIRONMENT ATTRIBUTES

Significant independent variables and the percent variance explained for each model developed using DMSV imagery and environmental attributes are given in Table 4. The column (Model PVE%) indicates the percent of variance explained in the distribution of the attribute from the data set used to develop the models. 'Order of split' indicates the level of the decision tree where the independent variable is used. The first order split is the variable which explains most of the variance of the dependant variable. All other splits are used in conjunction with the first split, describing increasingly smaller sets of the data. The first order split is usually highly significant (usually at the 99% level).

Table 4. Reliability and independent variables used in 'expert' models using DMSV and environmental variables.

Model	Dependant Variable	Model PVE %	Order of split	Independent variable	Significance	Order of split	Independent variable	Significance
<i>a. Species & land cover</i>								
2(i)	Dominant species	78.7	1	clu_b1med	0.0000	2	clu_b2on1	0.0158
			2	clu_b4med	0.0106	3	clu_b4on2	0.0357
			2	clu_b2on3	0.0017	3	clu_b4med	0.0107
			2	env_cti	0.0432			
3(i)	Soil	100	1	clu_b4on3	0.0000	2	clu_b2on1	0.0000
5(i)	E. sieberi percent	69.8	1	env_cti	0.0002	3	clu_b4on3	0.1511
			2	clu_b2on1	0.0037	3	clu_b2on3	0.0116
			2	clu_b3med	0.0007	3	clu_b2on3	0.0545
			2	clu_b2on1	0.0411	4	clu_b1med	0.0559
6(i)	Rainforest species percent	100	1	clu_b2on3	0.0000	2	clu_b4med	0.0000
7(i)	E. fastigata percent	98.7	1	clu_b3med	0.0000	3	env_cti	0.0599
			2	clu_b4med	0.0006	4	env_netrad	0.0000
			3	clu_area	0.0485			
8(i)	E. scias percent	56.9	1	env_cti	0.0089	2	clu_area	0.0052
9(i)	E. muelleriana percent	41.4	1	clu_b3med	0.0014	2	env_elev	0.0223
			2	clu_b4med	0.0098			
<i>b. Size and density</i>								
11(i)	Basal area 10-30 dbh	57.3	1	m6_rain	0.0321	2	clu_area	0.0128
			2	clu_b4on2	0.0001			
12(i)	Basal area 30-50 dbh	18.9	1	m2_dspect	0.0426	2	clu_area	0.0533
13(i)	Basal area 50-90 dbh	31.8	1	m9_muel	0.0208	3	clu_area	0.0243
			2	env_cti	0.0043	3	clu_b1med	0.0431

Model	Dependant Variable	Model PVE %	Order of split	Independent variable	Significance	Order of split	Independent variable	Significance
			2	clu_b2on3	0.0572			
14(i)	Basal area 90+ dbh	23.7	1	m1_spec	0.0097	3	clu_area	0.0383
			2	m9_muel	0.0232			
15(i)	Basal area 10+ dbh	32.3	1	m2_dspec	0.0020	4	clu_area	0.1125
			2	m9_muel	0.0124	4	env_cti	0.0785
			3	m7_fast	0.0206	5	clu_b2med	0.0009
c. Tree development index								
16(i)	TDI percent sapling / young	78.2	1	clu_b2on1	0.0000	2	clu_b2on3	0.0003
			2	clu_b2on3	0.0056	3	m8_scia	0.0004
			2	clu_b2on3	0.0527			
17(i)	TDI percent early / mature	15.3	1	m5_sieb	0.0156	2	clu_b2on3	0.1728
18(i)	TDI percent late mature	35.1	1	clu_b2on1	0.0001	2	clu_b2on3	0.1591
			2	m7_fast	0.0028			
19(i)	TDI percent stag	46.8	1	clu_area	0.0397	2	clu_b4med	0.0039
			2	clu_b4on3	0.0410			
d. Height								
10(i)	Maximum height	54.3	1	m7_fast	0.0004	3	m2_dspec	0.0032
			2	clu_area	0.0001	4	env_cti	0.0027
			2	m9_muel	0.0546			
20(i)	Height percent 10-20m	15.2	1	clu_b4on3	0.0124	2	clu_b2on1	0.0241
21(i)	Height percent 20-30 m	19.1	1	m8_scia	0.0020	2	m2_dspec	0.0129
22(i)	Height percent 30-40m	36.9	1	m2_dspec	0.0003	2	m8_scia	0.0177
			2	env_cti	0.0058	3	env_netrad	0.0216
23(i)	Height percent 40+m	54.6	1	m7_fast	0.0052	2	env_cti	0.0171
			2	clu_area	0.0000			

Each of these models were applied within the GRASSLAND GIS system resulting in spatial predicting of each of the dependant variables. Examples of these models are shown in Figures 8 to 10.

Soil (model 3i) and rainforest (model 6i) are the most simple species models with high PVE's of 100%. Both models use DMSV data only. All the other species models use environmental attributes. Compound topographic index is used at higher levels in the models than net radiation. The infrared (band 4) and red (band 3) DMSV bands are used most commonly in species models. The green (band 2) and blue (band 1) channels are mostly applied only as ratios (e.g., 2 on 1, 2 on 3).

In general, the models for the distribution of *E. scias* (model 8i) and *E. muelleriana* (model 9i) were not as reliable (based on PVE) as other species models. This is possibly due to the lack of clear environmental niches of these species. The remaining species all have clear environmental ranges (such as occurring on ridges as opposed to gullies) and possibly occur predominantly as dominant trees in clusters or as single tree clusters.

Modelled species distribution and cluster size (clu_area) were used most commonly in density and stem size models. The density models are of a lower reliability than species models. The most significant density / size model was for the prediction of density of trees 10-30cm (model 11i), which explained 57.3% of model variance. The ratios of band 2 on 3 (clu2on3) and the ratio of band 2 on 1 (clu2on1) were used extensively in development of tree development index models. The model for TDI percent sapling/young (model 16i) explained 78% of variance. Modelled species distribution, cluster area, and environmental attributes were used in development of height models. The PVE for all height models was lower than for species, density and size, and tree development index models.

MODELS PRODUCED USING AERIAL PHOTO INTERPRETATION ATTRIBUTES

Significant independent variables and the percent variance explained for each model developed using 1:25,000 aerial photo interpretation in Table 5.

Table 5. Reliability and independent variables used in "expert" models using API variables.

Model no.	Dependant Variable	PVE %	Order of split	Independent variable	Significance	Order of split	Independent variable	Significance
<i>a. Species & land cover</i>								
2(ii)	Dominant species	68.5	1	api_fors	0.0000			
3(ii)	Soil	n/s						
5(ii)	<i>E. sieberi</i> percent	55.3	1	api_fors	0.0000			
6(ii)	Rainforest species percent	78.2	1	api_fors	0.0000			
7(ii)	<i>E. fastigata</i> percent	62.3	1	api_fors	0.0000			
8(ii)	<i>E. scias</i> percent	12.9	1	api_fors	0.0037			
9(ii)	<i>E. muelleriana</i> percent	n/s						
<i>b. Size and density</i>								
11(ii)	Basal area 10-30 dbh	5.8	1	api_reg	0.1104			
12(ii)	Basal area 30-50 dbh	4.8	1	api_fors	0.1937			
13(ii)	Basal area 50-90 dbh	9.9	1	api_mat	0.0510			
14(ii)	Basal area 90+ dbh	17.8	1	api_size	0.1235			
15(ii)	Basal area 10+ dbh	19.5	1	api_sen	0.0021	2	api_size	0.0509
<i>c. Tree development index</i>								
16(ii)	TDI percent sapling / young	60.3	1	api_size	0.0000	2	api_reg	0.0001
			2	api_fors	0.0257			
17(ii)	TDI percent early / mature	9.2	1	api_size	0.0003			
18(ii)	TDI percent late mature	26.4	1	api_mat	0.0161			
19(ii)	TDI percent stag	n/s		n/s				
<i>d. Height</i>								
10(ii)	Maximum height	50.1	1	api_fors	0.0000	2	api_dist	0.0478
20(ii)	Height percent 10-20m	22.2	1	api_fors	0.0056	2	api_dist	0.0728
21(ii)	Height percent 20-30m	15.1	1	api_fors	0.0541	2	api_dist	0.0552
22(ii)	Height percent 30-40m	32.5	1	api_fors	0.0000			
23(ii)	Height percent 40+m	19.9	1	api_sen	0.0002			

The forest type variable (api_fors) was the only attribute tested in development of species models. Again the Rainforest species was most accurately mapped (78.2 PVE%) with *E. muelleriana* and Soil both unable to be significantly predicted using the input variables. The percent of variance explained by the *E. scias* was also low (12.9%). Several different variables were used for derivation of size and density models, in several instances, only at the 80% confidence level. Overall, size and density models were quite poor. For example, model 15(ii) explains only 19.5% of model variance. API_SIZE was one of the more important independent variables for predicting tree development index. The model for TDI percent sapling/young (model 16ii) explained 60.2% of variance. Forest type and disturbance attributes were the variables commonly used to explain height. The percent variance explained for maximum height (50.2% for model 10ii) was higher than any of the size and density or tree development index models.

COMPARISON OF DMSV AND API MODELS

Table 4 and Table 5 have been summarised in Table 6 which shows the average PVE% explained for each of the attribute groups for DMSV models and API models.

Table 6. Comparison of the average reliability of models produced from DMSV imagery and environmental attributes and models produced from 1:25,000 aerial photo interpretation datasets.

Type of variables	DMSV Model average PVE %	API model average PVE %	DMSV compared to API PVE %
a. Species	74.3	46.2	+28.1
b. Size & density	32.8	11.6	+21.2
c. Tree development index	43.9	24.0	+19.9
d. Height	36.0	28.0	+ 8.1
Overall	48.5	28.4	+20.2

This summary indicates that the PVE% of models produced using DMSV and environmental attributes is about 20% higher than API models. Overall, the DMSV models have an average PVE% of 48.5, compared to 28.4% for API models. Species models show highest gain (+28.1%) and height models show least gain (+8.1%). Size and density attributes were most difficult to model, explaining on average only 32.8% PVE for DMSV models and only 11.6 % PVE for API models.

CONCLUSIONS

The Spatial Integration Project has shown that the combined use of high resolution multi-spectral remotely sensed data, environmental data, field data, with intelligent algorithms and modeling techniques is technically feasible for mapping forest species and structure in an integrated manner. Delineation and subsequent modeling of tree clusters from high resolution imagery is an integral component of this methodology. GIS datasets of topographic and climatic attributes are also an essential component of the technique. The study indicates that four band, two meter airborne DMSV data appears to be an adequate source of airborne remote sensing data.

The results presented in this paper indicate that the reliabilities for predicting most forest attributes is substantially higher than can be achieved using standard procedures for interpretation of 1:25,000 aerial photographs. This is primarily due to (i) the high resolution of the input datasets with tree clusters occurring at a much finer scale than the more familiar API polygons; (ii) the use of multi-spectral information about the forest canopy, and (iii) the inclusion of high resolution terrain and climatic data sets.

At this stage of the project only limited remote sensing attributes for each cluster were included in the modeling framework. Future research will concentrate on evaluating the inclusion of additional image attributes (e.g., variance) on the reliability of models. Likewise the applicability and delineation of tree clusters requires additional research with respect to their contribution to image analysis and their role in estimating actual crown size and area. It will also be useful to review the use of alternative field parameters and modeling techniques for associating field measures with remote sensing and environmental data sets. These studies will need to also account for trees which can not be clearly associated with tree clusters. One approach will be to seek to model the same attributes for both clusters and for plots or stands. There is also a need to verify the reliability of both DMSV and API models using independent data sets based on plots rather than clusters.

Future studies will need to concentrate establishing readily applicable techniques for associating trees measured in the field with clusters delineated from remote sensing imagery. One possible approach is to acquire higher resolution imagery (e.g., orthophotos) at the same time as digital multi-spectral imagery. Large scale orthophotos could then be used in field surveys to assist with location of upper stratum trees.

Before these techniques can be applied for large areas, current limitations in achieving cost-effective image mosaicing and registration techniques will be required. This again may require collection of higher

resolution aerial imagery which can be processed using ortho photography techniques. New high resolution satellite sensors provide a feasible option for cost-effective image acquisition. Operational adoption of these techniques would also require further modularization of all techniques and additional software development to ensure software tools are robust and accessible.

Despite these operational restraints the research presented in this paper is sufficient to indicate that an entirely new approach to forest mapping is becoming available. Mapping of detailed forest attributes, based on tree clusters from high resolution imagery, will require a major rethink of procedures for mapping, monitoring and field assessment of forests. This new approach will be reliant on the integrated assessment of forest species and structure. Before these techniques can be considered for operational use, their applicability will need to be tested at a range of forest types, and effort put into addressing cost, timing, and more detailed studies to review model reliability.

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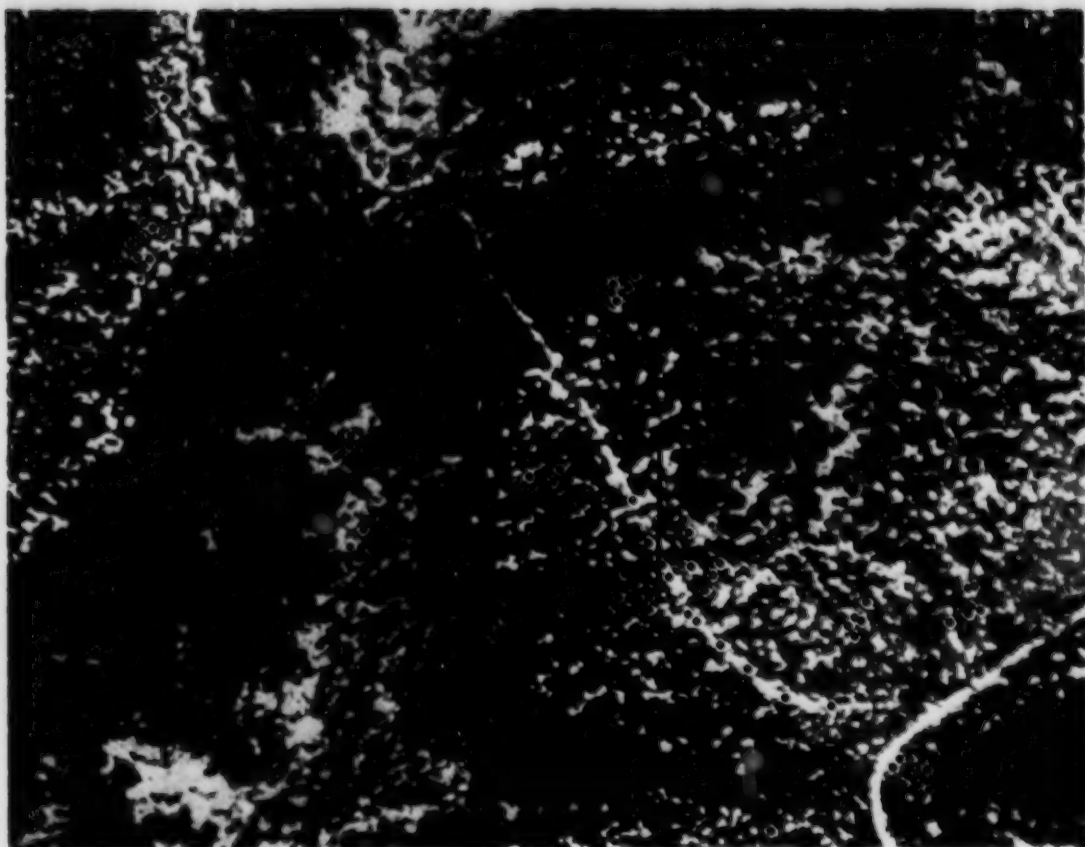


Figure 1. *DMSV mosaic of the Dingo study area which is 1.1 km x 0.8 km. Imagery was acquired by SpecTerra Systems (Perth, Australia) using a 4 camera digital multi-spectral video (DMSV) system. Imagery was registered to control points produced from triangulation of 1:15,000 aerial photographs. The image has also been corrected for BRDF and hotspot effects. The black box shows the extent of a sub-area used in later illustrations. Location of field sites which record individual tree attributes (species, size, height, tree development index) are shown as black dots. Data for 98 tree clusters at 17 separate plot locations are shown. An addition 10 soil sites along the road were also selected. Primary access to the site is from the gravelled road (Dingo Road) running along the ridge-top from the lower right to the upper center part of the image. The highly reflective crowns of *E. sieberi* occur either side of the road. Rainforest trees are yellow and orange as seen at the bottom of the drainage lines. Large *E. cypellocarpa* and *E. fastigata* cover the south facing slope on the top left of the image. Other trees are mainly *E. scias*.*

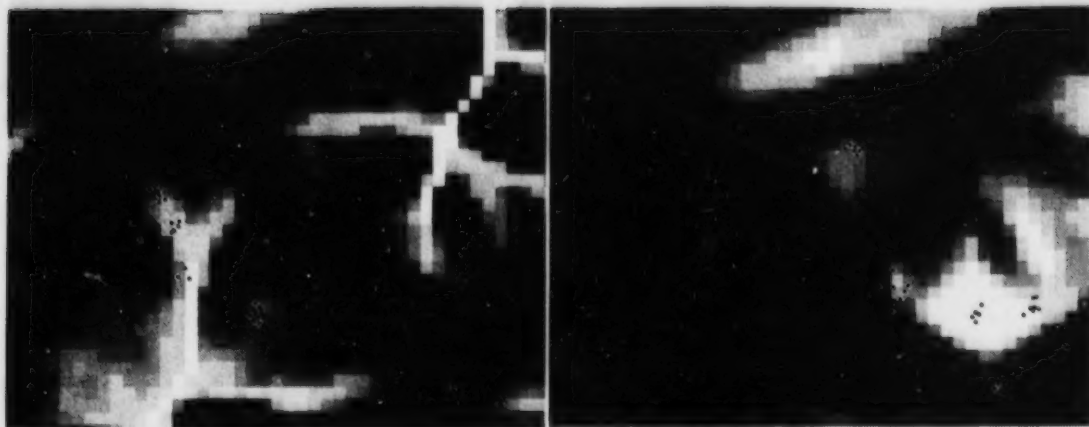


Figure 2. Compound topographic index (left) and net radiation (right) surfaces of the study area at 25m grid resolution generated from 1:25,000 scale contours and streamline data.

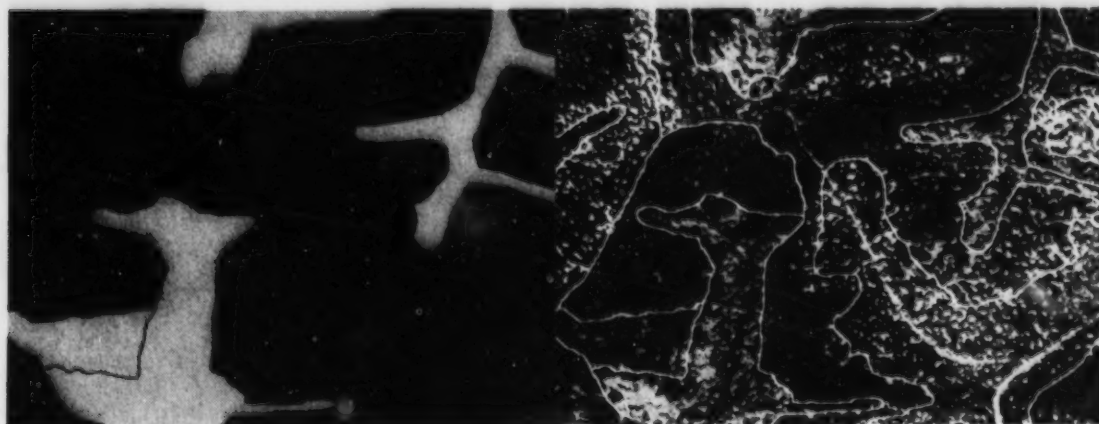


Figure 3. Forest mapping drawn from manual interpretation of 1:25,000 colour stereo aerial photographs using current regional mapping standards. The left image shows individual polygons, coloured according to overstorey composition type. The right image illustrates the boundaries overlaid on the DMSV mosaic.



Figure 4. Examples of tree clusters. The cluster on the left is composed of four early mature *E. sieberi* trees between 30cm and 50cm dbh. The cluster on the right consists of two late mature trees, one *E. cypellocarpa* and one *E. fastigata*, between 100 and 120cm dbh.

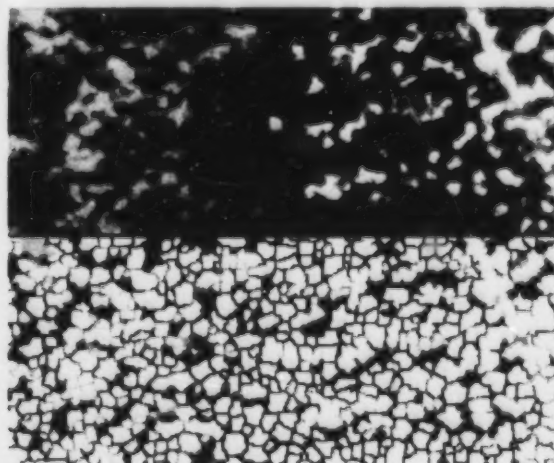


Figure 5. The lower image shows tree clusters delineated using TIDA for a subset of DMSV imagery from the centre of the study area (see box in Figure 1) measuring about 350m x 150m. This extract spans rainforest (on the left) through mixed eucalypt forest and to a gravel road (on the right).

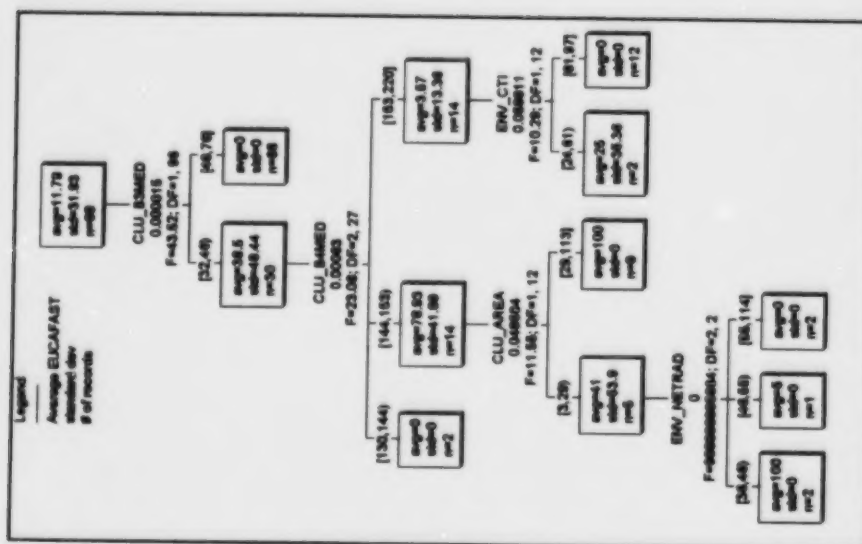


Figure 6. An example of a decision tree which relates field data (percent composition in a cluster of *E. fastigata*) to spectral and spatial attributes of the cluster and environmental attributes. The model indicates how most of the variance of distribution of *E. fastigata* is explained by band 3 of DMSV data (clu_b3med), shown as the first 'split' of the data. The 98 observations in the data set are partitioned into two sets depending on whether their band 3 value is above or below 46 DN values. The 68 observations of *E. fastigata* have an average composition of 38.5 percent of *E. fastigata*. The other 30 observations have an average composition of 44.44 percent of *E. fastigata*. Other variables which are similarly divided are DMSV band 4 (clu_b4med), the size of clusters (clu_area), compound topographic index (env_cti), and net radiation (env_netrad). Where the model is not able to further divide a node to explain the distribution of *E. fastigata* more precisely, this node is referred to as a 'leaf node'.

```

RULE_1 IF ENV_NETRAD = [36,46)
        CLU_B4MED = [130,153)
THEN EUCAFAST = 100; std=0

RULE_2 IF ENV_NETRAD = [36,46)
        CLU_B4MED = [153,220]
THEN EUCAFAST = 0; std=0

RULE_3 IF ENV_NETRAD = [46,55)
        CLU_B2ON1 = [111,128)
THEN EUCAFAST = 100; std=0

RULE_4 IF ENV_NETRAD = [46,55)
        CLU_B2ON1 = [128,162]
THEN EUCAFAST = 6.1111;
std=16.541

RULE_5 IF ENV_NETRAD = [55,114]
        CLU_B2ON3 = [108,149)
THEN EUCAFAST = 0; std=0

RULE_6 IF ENV_NETRAD = [55,114]
        CLU_B2ON3 = [149,196]
THEN EUCAFAST = 20; std=44.721

```

Figure 7. An example of decision rules produced by Knowledge Seeker for the decision tree presented in Figure 6. These rules can be translated into a format suitable for implementation in a GIS/IPS. Each rule (there are six rules in this example) explains the combination of independent variables required to predict the distribution with a 'leaf node' of the decision tree. These rules are applied to the full study area to predict the distribution of these attributes across the landscape. In this example, EUCAFAST 100 means that 100% (of the basal area) of the cluster is predicted to be *E. fastigata*. STD is the standard deviation of the estimate.



Figure 8. Species models based on DMSV and environmental data. The left frame shows the percentage composition of *E. sieberi* (model 5) (69.8 % PVE). The right frame shows the percentage composition of rainforest species (model 6) (100% PVE). Clusters which have a high density of the modelled species are white and clusters with a low density are black. The background for this image is a 25m-resolution elevation model. Dark areas are at lower elevation. The higher elevation ridges are white.



Figure 9. Size and density models based on DMSV and environmental data. The left frame shows the percentage density of small trees of dbh 10-30 cm (model 11) (57.3 % PVE). The right frame shows the percentage density of large trees of dbh 90+ cm (model 14) (37.3% PVE). Clusters with a high density in the size class are white. Clusters with a low density in that size class are black.

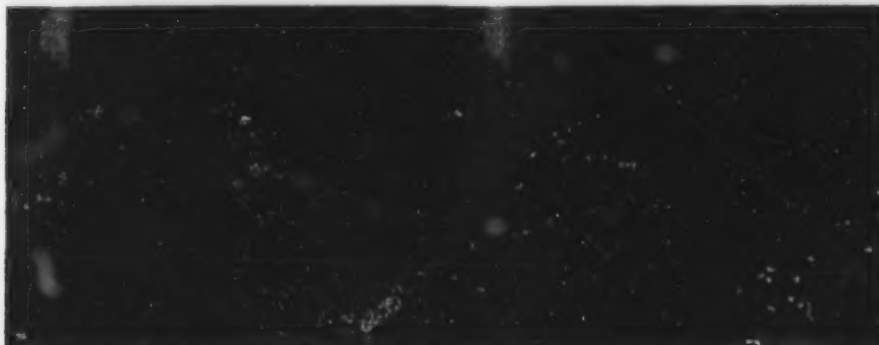


Figure 10. Tree development index models based on DMSV and environmental data. The left frame shows the percentage density of sapling/young trees (TDI 1-5) (model 16) (78.2 % PVE). The right frame shows the percentage density stags (TDI 14-19) (model 19) (46.8% PVE). Clusters with a high density in the tree development class are white. Clusters with a low density in that tree development class are black.

AN EVALUATION OF THE RELATIVE VALUE OF SPECTRAL AND PHENOLOGICAL INFORMATION FOR TREE CROWN CLASSIFICATION OF DIGITAL IMAGES IN THE EASTERN DECIDUOUS FOREST

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ABSTRACT

Digitized, multitemporal, small format 35 mm aerial photography was used to determine the relative value of spectral and phenological information for tree crown classification of digital images of the Eastern Deciduous Forest. This sampling scheme was designed to simulate the high spatial resolution and multitemporal data anticipated from the next generation of land observing satellites. The one-hectare study site, located in the West Virginia University Experimental Forest approximately 15 km east of Morgantown, West Virginia, was photographed from a light aircraft 10 times from May to October 1997 using both true color and false color film. All negatives of the plot were digitized, rectified, enhanced, and classified using ERDAS Imagine. Differences in the timing of phenologic events between tree species, specifically leaf development and flushing, leaf maturity, and leaf senescence, made it possible to separate spectrally four deciduous tree species, namely *Liriodendron tulipifera*, *Acer rubrum*, *Quercus rubra*, and *Quercus alba*, from the surrounding vegetation in the test plot. Optimally timed photography was required during spring and autumn to coincide with seasonal variations in leaf phenology between deciduous species. Within the visible spectrum (400-700 nm), spectral differences in tree crowns were observed based at least partly on leaf ontogeny and primary leaf pigments. In contrast, near-infrared (700-900 nm) reflectance was influenced primarily by plant tissue characteristics (Boyer *et al.*, 1988). However, color IR produced a wide range of foliage colors which, when combined with selected bands (multi-date) of the visible spectrum, made a significant contribution to the separation of some individual tree species. Photography acquired in spring and fall provided the best data for species separation. Variable canopy illumination made digital classification of individual trees complex.

Keywords: aerial photography, small format, multitemporal, multispectral, phenology, classification.

RÉSUMÉ

ÉVALUATION DE LA VALEUR RELATIVE DE L'INFORMATION SPECTRALE ET PHÉNOLOGIQUE AUX FINS DE LA CLASSIFICATION DES HOUPPIERS À PARTIR D'IMAGES NUMÉRIQUES DE LA FORÊT DÉCIDUE DE L'EST DE L'AMÉRIQUE DU NORD

Des photos aériennes multitemporelles numérisées de petit format (35 mm) ont servi à déterminer la valeur relative de l'information spectrale et phénologique aux fins de la classification des houppiers de la forêt décidue de l'est de l'Amérique du Nord. Le modèle d'échantillonnage retenu avait pour but de simuler la haute résolution spatiale et les données multitemporelles que devraient fournir la prochaine génération de satellites d'observation de la Terre. Le site d'étude d'un hectare, situé dans la West Virginia University Experimental Forest à environ 15 km à l'est de Morgantown (Virginie-Occidentale) a été photographié à 10 reprises à bord d'un avion léger entre les mois de mai et octobre 1997 sur pellicules couleur, vraies et fausses. Tous les négatifs de la parcelle ont été numérisés, corrigés, accentués et classés à l'aide de l'ERDAS Imagine. Comme les phénomènes phénologiques associés aux diverses espèces d'arbres, notamment le développement, la pousse, la maturation et la sénescence des feuilles, se produisent à des moments différents, il a été possible d'isoler, au plan spectral, les quatre espèces de feuillus suivantes – le tulipier d'Amérique (*Liriodendron tulipifera*), l'érable rouge (*Acer rubrum*), le chêne rouge (*Quercus rubra*) et le chêne blanc (*Quercus alba*) – de la végétation avoisinante dans la parcelle à l'étude. Les photos devaient être prises aux périodes les plus propices, soit au printemps et en automne, pour saisir les variations phénologiques saisonnières des feuilles de diverses espèces de feuillus. Dans la région visible du spectre (400-700 nm), des différences dans les valeurs spectrales pour les houppiers ont été observées, du moins partiellement au niveau de l'ontogenèse foliaire et des pigments des feuilles primordiales. À l'opposé, la réflectance proche infrarouge (700-900 nm) a surtout fait ressortir les caractéristiques des tissus végétaux (Boyer et coll., 1988). Cependant, l'infrarouge couleur a fait apparaître un large éventail de couleurs de feuillage qui, combinées à certaines bandes (multidates) de la région visible du spectre, ont largement contribué à la distinction de certaines espèces d'arbres. Ce sont les photos prises au printemps et en automne qui ont fourni les données les plus utiles à la séparation des espèces. Les variations dans l'illumination du couvert forestier ont compliqué la classification numérique des arbres individuels.

INTRODUCTION

Remotely sensed data has four main characteristics that define its resolution and scale: spatial, spectral, temporal, and radiometric. Although there is a general trend of improvements in the resolution of each of these attributes, most modern sensors are designed to exploit only one of the attributes. For example, the movement toward high spatial resolution imagery can be seen over the last 25 years from the introduction of Landsat Multispectral Scanner (MSS) in 1972 with 79 meter resolution through Landsat Thematic Mapper (TM) with 30 meter resolution (Lauer, *et al.* 1997), and finally to the more recent Systeme pour l'Observation de la Terre (SPOT) sensor with 20 meter multispectral and 10 meter panchromatic resolution respectively. In addition, several new sensors with one to five meter spatial resolutions have recently been deployed, or are scheduled for deployment within the next few years. Like the spatial resolution trend, the shift toward hyperspectral imagery has evolved from the introduction of Landsat MSS, which collected data in four relatively broad spectral bands, to current hyperspectral sensors like the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) and the Hyperspectral Digital Imagery Collection Experiment (HYDICE), both of which collect data in over 200 contiguous bands. The recently failed Lewis, a satellite-borne sensor built by TRW, was designed for hyperspectral imaging in 384 narrow wavebands in both the visible and infrared regions of the electromagnetic spectrum. Data sets with significant multi-temporal resolution, such as those collected by the Advanced Very High Resolution Radiometer (AVHRR), are normally acquired with only a limited number of bands, but with a short sensor revisit time. Such data provide the potential for classification based on phenological information over large areas.

This shift in research focus raises several questions as to which type of data is best for species-level tree crown classification of digital imagery—hyperspectral data consisting of one scene and many bands, multi-

temporal data consisting of many different scenes and fewer bands, very high spatial resolution panchromatic images, or perhaps an intermediate combination of the three. This paper will examine the relative importance of spectral and phenological information derived from multi-temporal data sets and how these two characteristics combined with high spatial resolution are related in terms of digital imagery classification accuracies for tree crown classification in the Eastern Deciduous forest.

METHODS

STUDY SITE

The one-hectare study site is located in the West Virginia University Forest approximately 15 km east of Morgantown, West Virginia. The Forest consists of approximately 3,040 hectares (7,600 acres) and is centered on the northeast-southwest trending Chestnut Ridge Anticline which is the westernmost major anticline in the Appalachian Plateau (Fenneman 1983). The study site is situated on the western side of the anticline giving it a northwestern exposure. The minimum and maximum relief of the site are 426 meters (1,420 feet) and 444 meters (1,480 feet) respectively. Despite the elevation, the site is moist due primarily to its exposure, gentle slope, and the dissection of the surrounding area by two stream channels—one intermittent stream and one permanent stream. The site was last logged between 60 and 70 years ago leaving only a few residual white and red oaks. The present forest on the site is classified as an Appalachian mixed hardwood forest type. Yellow-poplar, white oak, and northern red oak comprise more than 50% of the tree species on the study site. The forest floor is dominated by greenbrier (*Smilax glauca*), bracken fern (*Pteridium aquilinum*), and cinnamon fern (*Osmunda cinnamomea*).

GROUND DATA

The site was inventoried in July 1996 using a Criterion 400 Survey Laser. The primary data collected during the inventory consisted of the site boundaries, identification of individual tree species and their relative locations within the plot, tree height, diameter breast height (dbh) at 1.3 meters above the ground, and individual tree crown measurements. Only trees with a dbh greater than approximately 10 cm (four inches) were included in the inventory. The raw ground data was later converted to digital format and used to generate a vector coverage showing tree species, relative locations, and individual tree crown shapes as viewed from the ground.

The one-hectare site contained 402 trees. Yellow-poplar (*Liriodendron tulipifera*), white oak (*Quercus alba*), and northern red oak (*Quercus rubra*) dominate the upper canopy (21 meters) and make up approximately 63% of the tree species on the site. Red Maple (*Acer rubrum*) is also well represented on the site (30% of the tree species) and comprises the vast majority of the intermediate and overtopped crown classes. Other associates such as basswood (*Tilia americana*), blackgum (*Nyssa sylvatica*), black cherry (*Prunus serotina*), red elm (*Ulmus rubra*), sweet birch (*Betula lenta*), black walnut (*Juglans nigra*), and chestnut oak (*Quercus prinus*) make up the remaining 7% of the tree species on the site and, with few exceptions, are also relegated to the lower crown classes.

PHOTOINTERPRETATION

The ground data had two important limitations: (1) the ground data did not assess which trees were overstory trees, and (2) the surveyed shapes of the tree crowns were approximated based on crown radii measured in four cardinal directions. Therefore, a stereo photointerpretation was carried out, drawing extensively on the ground data, to produce a highly accurate overstory canopy map. A digitized vector coverage was generated from the photo interpretation and imported into ERDAS *Imagine*. The summary data from the photointerpretation are listed in Table 1.

PHENOLOGY

Phenology is considered a much broader topic today than in the past. Historically, the term phenology has usually referred to specific agricultural events such as planting, emergence, fruiting, and harvest (Reed *et al.*

1994). The US International Biological Program Phenology Committee defines phenology as "the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species." (Lieth 1974, Reed *et al.* 1994). The committee also expanded the definition of seasonality to include "the occurrence of certain obvious biotic and abiotic events or groups of events within a definite limited period or periods of the astronomic (solar, calendar) year" (Lieth 1974, Reed *et al.* 1994). Due to advances in remote sensing capabilities and techniques, much research in phenology over the last twenty years has focused on the monitoring of phenological events at a variety of scales. More recently, some researchers have concentrated on the measurements of plant cover and productivity (Tucker and Sellers 1986) while others have focused on the development of complex phenological models (Lüdeke *et al.* 1991, Sellers *et al.* 1992) and the measurement of phytophenological variables such as day-length, air temperature, and water availability (Lloyd 1990). It is well documented that phenology varies by species and is influenced by such factors as photoperiod, soil moisture, soil temperature, air temperature, and solar illumination (Sayn-Wittgenstein 1978, Thomas and Stoddart 1980, Caprio 1966). However, some researchers have concluded that, despite these seasonally varying environmental conditions, the interannual variability of phenology measurements is relatively low because the photosynthetic activity of deciduous forests is highly dependent on photoperiod and temperature—both of which are relatively stable (Reed *et al.* 1994). Despite this relative interannual stability, phenology can vary from year to year. For example, foliar senescence in 1997 at the study site was somewhat different from preliminary measurements conducted in 1996. The development of colored pigments anthocyanins, carotenoids, and xanthophylls was not a gradual process and there was not a noticeable peak in fall foliage coloration. Leaf abscission and death occurred rapidly during the first two weeks of November 1997.

One critical aspect of this study was to identify basic phenological and seasonality differences between yellow-poplar, red maple, red oak, and white oak. For example, the order of leafing, the characteristics of the spring, summer and fall foliage, flowering and fruiting, fall senescence, and the order of leaf-fall are all of potential value for discriminating individual tree species. Although these tree characteristics are variable and depend on many factors, they were used as a general guideline to obtain and interpret the optimally-timed photography. Phenological events in the forest were also used to assist in the site photointerpretation.

IMAGE ACQUISITION AND PROCESSING

Two Nikon F4 35mm cameras fitted with 35-70 mm zoom lenses and multi-databacks were used to acquire the large-scale, small format aerial photography. Both cameras were securely attached to an adjustable, window-mounted, dual-camera mount designed for light, high-wing aircraft. The platform used for acquiring the aerial photography was a Cessna 172 Skyhawk traveling at approximately 90 knots. One important part of this research was the multispectral component. Before mounting, each camera was fitted and loaded with its own complement of film and filters. For normal color aerial photography, the first camera was fitted with a UV filter and loaded with Kodak Gold 100 normal color film. The three layers of this film have maximum spectral sensitivity at approximately 470, 540, and 630 nm, and a generous exposure latitude from two stops underexposure to three stops overexposure. The second camera was loaded with Kodak Ektachrome Infrared EIR film. This infrared-sensitive reversal film is sensitive to radiation from about 700 to 900 nm as well as radiation in the visible portion of the spectrum. A Wratten #12 Deep Yellow filter was used in conjunction with the EIR film to ensure only infrared, green, and red radiation reached the film layers as well as eliminate haze. Unlike the normal color film, the EIR film's exposure latitude is limited to $\pm 1/2$ stop making the choice of exposure and aperture much more critical.

Each of the 10 flights in 1997 followed one basic flight plan (see Table 2 and 3) using the same air survey and mapping calculations (Warner *et al.* 1996). The focal length of the cameras was set to 70 mm to give the greatest magnification and thus help reduce topographically induced scale variation. This continuity between flight missions was critical for the multitemporal analysis of the images. Despite the continuity and the longer focal length, scale differences between dates were inevitable due to differences in flying height and flight lines. The flight line was based on visual navigation and crossed the study site from north to south. Three 6m x 9m (20' x 30") blue tarps were used to mark the northwest, southwest, and southeast corners of the plot. After experimenting with LORAN and GPS navigational aids, it was found that the most accurate way of repeating the flight path was to use visual navigation. All photographs were acquired between 11:30 a.m. and 1:30 p.m. on cloudless days to maximize incoming solar radiation on the study site. Phenological events, combined with

local weather conditions, were the two primary factors which influenced the timing of the aerial photography. In addition to the small-format aerial photography, a large-format, normal color stereotriplet of the study site was acquired on October 6, 1997 by Air Photographics, Inc. in Martinsburg, West Virginia at a scale of 1:2,000. This photography was acquired with a mapping camera and therefore had superior geometric fidelity compared to the 35 mm photography. Once in digital format, the center photograph served as a base image to which all 19 small format digital images were rectified.

Using a Microtek Scanmaker 35t Plus slidescanner and Adobe Photoshop, each negative and positive was scanned at 3,000 dpi with 24 bit resolution. Each image was then exported to ERDAS *Imagine* for image processing. Once in *Imagine*, each of the 19 three-band images was enhanced and registered to the base image. For comparison purposes, the ground data was also registered to the base image and overlaid on each image. Several small gaps in the site coverage necessitated the scanning, enhancing, rectifying, and mosaicking of an additional five images. These gaps in coverage were a result of aircraft tilt and navigational error while photographing the study site. Finally, the stacked images were resampled by pixel aggregation to a coarser scale to reflect the basic accuracy of the co-registration and provide a uniform spatial resolution between images. Another advantage of resampling was a smaller file size which allowed faster processing.

CLASSIFICATION

Selecting training samples that best represented the desired classes was an iterative process. Statistics, histograms, signature separability, and a contingency matrix were used to evaluate the signatures. The maximum likelihood decision rule was used for all classifications. The final classification scheme consisted of training samples from 12 classes. More than one signature was required for each class because no one training sample could represent the spectral variation within a species. Variations in the viewing angle, sun angle, and phenology resulted in several distinct signatures both within and between species. Because of the large difference in species representation on the study site, probability factors were assigned to each signature based on known percentages of canopy cover. All signatures were created from supervised training and were verified using the ground data, digitized photointerpretation, and field checking.

Because the data set consisted of 60 bands of data representing 11 different dates, a systematic classification approach was developed to investigate the major patterns and help determine which combination of bands and dates might provide the best classification accuracies and help assess the relative value of multitemporal versus multispectral and color versus color infrared data. A fundamental goal of this study was the delineation of individual tree species. Therefore, the accuracy assessment for all classifications was determined at the tree level rather than at the pixel level. This approach, however, assumes that an automated procedure for the isolation of individual tree crowns could be used. Several researchers have developed and tested different approaches for isolating individual trees in the forest canopy—each with varying success (Ballard 1981, Gougeon 1993, Zeidenberg 1990). Gougeon (1993) concluded that the recognition and isolation of individual tree species may lie in the development and testing of new image analysis tools which, when used in conjunction with an expert or knowledge-based system, could provide the means for an automated forest inventory system. Additionally, other research has determined that the "traditional" pixel-based approach to classification, especially of high spatial resolution data, is not the most useful (Trietz *et al.* 1985, Gougeon 1993, Crane *et al.* 1972). Gougeon (1993) developed and experimented with several multispectral classification approaches where the object of classification was the tree crown rather than the individual pixel. We plan to use an aspect of these classification strategies on this data set in lieu of the traditional pixel-based approach in future analysis (see also the paper by Warner *et al.* 1998 in this same volume).

ACCURACY ASSESSMENT

In this study, one accuracy assessment model was used to assess the classification accuracies in three different ways. All three methods involved a pixel to pixel comparison where pixels in the classified images were compared to a polygon overlay representing the ground truth. The first two methods were basically identical, however, one method used the training samples in the accuracy assessment while the other did not. Finally, the third method assessed each tree crown independently. A tree was considered correctly classified if over 50% of its crown was classified correctly.

RESULTS AND DISCUSSION

The accuracy assessment results in this paper are preliminary and should be interpreted accordingly (see Table 4). These band combinations include: a multitemporal normal color data set consisting of 33 bands; a multitemporal infrared-only data set consisting of nine bands; a multitemporal data set consisting of all 11 normal color blue bands; two multitemporal data sets including bands from spring, summer, and fall—one set consisting of normal color and the other with normal color and color infrared; two single-date data sets from the spring—one three-band normal color and one six band normal color and color infrared data set; and finally two fall data sets—one with three bands of normal color and the other with the same three normal color bands plus the infrared band.

Additional testing and evaluating is needed to fully understand the relative value of the different resolutions. However, despite the limited number of combinations reported, patterns in the data suggest that temporal resolution, spectral resolution, and phenological information are all important factors in classifying individual tree species. For example, the best classification accuracy for yellow-poplar was achieved by using a multitemporal data set consisting of all color bands (see Figure 1), however, this species was also classified at 80% with a single-date normal color image from October (see Figure 2). This suggests that temporal resolution as well as phenology, specifically the influence of leaf pigments during fall senescence, helped make this species spectrally different from surrounding species. Likewise, red maple had significantly higher accuracies using the single-date fall bands 52, 53, 54, and 55 due to leaf pigments and internal leaf structure (see Figure 3). Red maple was also the only species that responded favorably to the multitemporal all-infrared band combination. In contrast, the inclusion of infrared bands, either alone or in conjunction with normal color bands, did not appear to help the classification accuracy of yellow-poplar. When the infrared band 55 was added to the normal color bands 52, 53, and 54 classification accuracies dropped significantly (see Figure 2). The same happened when the color infrared bands (four, five, and six) were added to the normal color bands one, two, and three from the spring. The lowest accuracies for yellow-poplar were recorded when the multitemporal infrared band data set was used in the classification. White oak is another species that displayed increased classification accuracies using both multitemporal normal color and normal color/color infrared band combinations, specifically the band combinations from May, August, and October (see Figure 4) and the multitemporal data set containing all color bands (see Figure 1). Additionally, the May 23rd normal color and color infrared bands (1-6) provided higher accuracies than the normal color bands (1-3) from the same date. This increased accuracy is probably due to phenology. Leaf flushing on many of the white oaks occurred late in May which provided a brief window of opportunity to spectrally separate some individuals from surrounding species. Like the white oaks, the red oaks also had increased classification accuracies using both the normal color and color infrared bands (bands 1-6) from May 23rd (see Figure 5) and the multispectral May (bands 1-6), August, (bands 19-24), and October (bands 37-42) data set. It is interesting to note that in all the classifications done in this study, these two multitemporal band combinations were the only time that both species were spectrally similar. Should both red oak and white oak be combined into one class, the classification accuracy for oaks would rise to an average of 76% using these band combinations.

CONCLUSIONS

Although the results are preliminary, the comparison of these multitemporal and multispectral band combinations for species classification of individual tree crowns shows that:

- Vignetting has a significant effect on classification accuracies. The darkened areas around the edges of the images significantly degraded classification accuracies. One solution to this problem would be to acquire the photography at a scale that centers the area of interest in the middle of the photograph, or perhaps crop the image to remove the darkened edges. Alternatively, adaptive filters could be applied to suppress the vignetting.
- Variable canopy illumination made the classification of tree species very complex. For example, red oak and red maple signatures were often confused due to shadow. The red maple trees that were visible from above were mostly located around canopy gaps. Shadow problems with red oak were primarily caused by

its somewhat open crown structure and stout branching. Slight registration errors between bands of different dates as well as natural canopy phenology over the course of the year also introduced shadow.

- Mosaicking images should be avoided because of possible tone and contrast variations between consecutive photographs in the same flight line. Uneven exposure and film processing appeared to be the primary cause of this problem.
- Spring photography is critical to capture species phenology. The first flight for this study occurred on May 23rd which was timely for white oak leaf-out, however, a flight just two or three weeks earlier would have been optimal for red maple flowering and leaf-out. In this case, overcast weather conditions prevented earlier flights.
- The value of infrared in species classification depends on the species. Classification accuracies for yellow-poplar declined with the introduction of infrared bands while red maple accuracies improved significantly (see Table 4, Figure 2, and Figure 3).
- The classification of the oak species was also sensitive to the inclusion of the color infrared bands. In the spring multispectral data set (bands 1, 2, and 3), the inclusion of the infrared bands four, five, and six increased the accuracy for both white oak and red oak (see Table 4 and Figure 5). In contrast, the addition of only the infrared band 55 in the fall multispectral data set (bands 52, 53, and 54) significantly increased the classification accuracy for red oak, but not for white oak.
- Classification accuracies using multitemporal data sets with selected band combinations compare favorably with accuracies achieved using single-date multispectral data sets.
- Phenology plays an important role in digital tree species identification. Seasonal variations in leaf phenology provided the best discriminant between the four deciduous species.

Future concerns will focus on the selection and testing of new signatures as well as experimenting with different classification and post-classification methods and techniques. A systematic approach to band and date selection will also be developed and used to help identify unique band and/or date combinations which improve classification accuracies. Although the classification accuracies in Table 4 are relatively low for most species, the results from the combination of bands tested so far have demonstrated that temporal resolution, spectral resolution, and phenology can be exploited by species to help improve classification accuracies.

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Species	Number of trees	Percent upper canopy area
Yellow-poplar	101	60%
White oak	11	10%
Red oak	21	10%
Red maple	15	2%

Table 1. Photointerpretation results.

Scale of negatives	1:6000
Photograph scale	1:1415
Ground coverage of negative (36mm side)	212 m (708 ft)
Ground coverage of negative (24mm side)	142 m (472 ft)
Flying height above mean seal level	892 m (2976 ft)
Flying height above ground level	413 m (1376 ft)
Intervalometer setting	1 second
Ground distance between conjugate principal points	51 m (169 ft)

Table 2. Selected flight data from May to October 1997.

Flight Dates	Normal Color Band Numbers			Color Infrared Band Numbers		
	Red	Green	Blue	Infrared	Red	Green
05/23/97	1	2	3	4	5	6
06/23/97	7	8	9	10	11	12
07/17/97	13	14	15	16	17	18
08/08/97	19	20	21	22	23	24
09/05/97	25	26	27	28	29	30
09/19/97	31	32	33	34	35	36
10/02/97	37	38	39	40	41	42
10/11/97	43	44	45	46	47	48
10/23/97	49	50	51	-	-	-
10/30/97	52	53	54	55	56	57
10/06/97*	58	59	60	-	-	-

Table 3. Flight dates and band information for the full data set (* denotes base image to which other bands were co-registered). Cells with no band numbers (-) indicate no data was collected on that date.

Band	Tree Species Accuracy (%)											
	Yellow-Poplar			White Oak			Red Oak			Red Maple		
Combinations	A	B	C	A	B	C	A	B	C	A	B	C
All Normal Color Bands	72	72	83	68	61	62	52	46	44	52	34	31
All Color Bands	73	72	85	82	77	75	37	28	17	50	31	31
All Infrared Bands	40	39	30	30	23	0	39	35	28	57	44	62
All Blue Bands	56	56	64	59	50	63	36	28	11	46	28	23
Bands 1-3, 19-21, 37-39	57	55	63	60	50	50	60	56	55	39	18	8
Bands 1-6, 19-24, 37-42	52	50	57	71	64	63	62	57	61	40	18	0
Bands 1-3	60	59	69	55	46	63	48	43	39	29	11	1
Bands 1-6	56	55	63	69	61	63	54	49	50	27	6	0
Bands 52-54	71	71	80	18	13	0	8	4	0	61	53	61
Bands 52-55	61	60	62	33	23	0	30	24	11	66	58	62

Table 4. Selected multispectral and/or multitemporal band combinations (see Table 3 for band details).
Column A = Percentage of correctly classified pixels per species (with training data).
Column B = Percentage of correctly classified pixels per species (without training data).
Column C = Percentage of correctly classified trees per species (without training data).

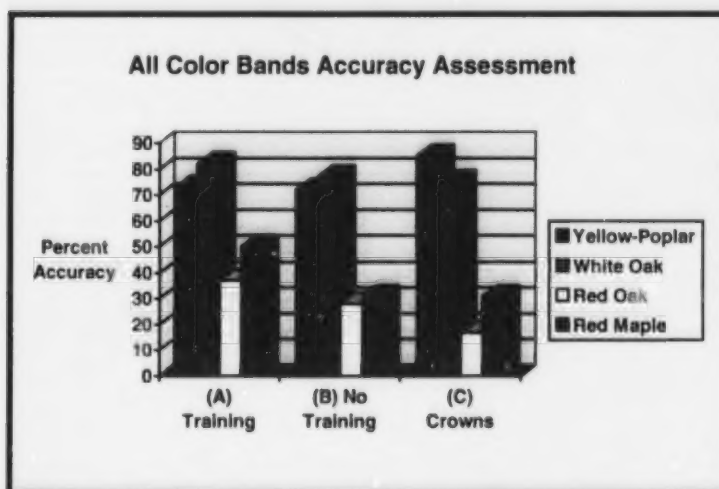


Figure 1. Accuracy assessment for yellow-poplar, white oak, red oak, and red maple using methods A, B, and C. This classification used all visible bands from the true color images and two visible bands from the CIR images (51 bands total). Note the increase in classification accuracies over the classification using only the true or normal color bands.

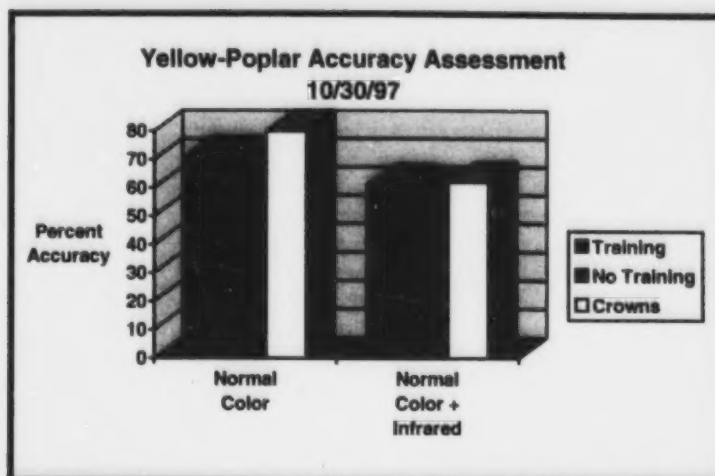


Figure 2. Accuracy assessment for yellow-poplar. This accuracy assessment compares two different band combinations for October 30, 1997. The first combination uses three bands of normal or true color while the second classification uses the same three bands plus the infrared band. Note the decrease in accuracy for yellow-poplar with the introduction of the infrared band.

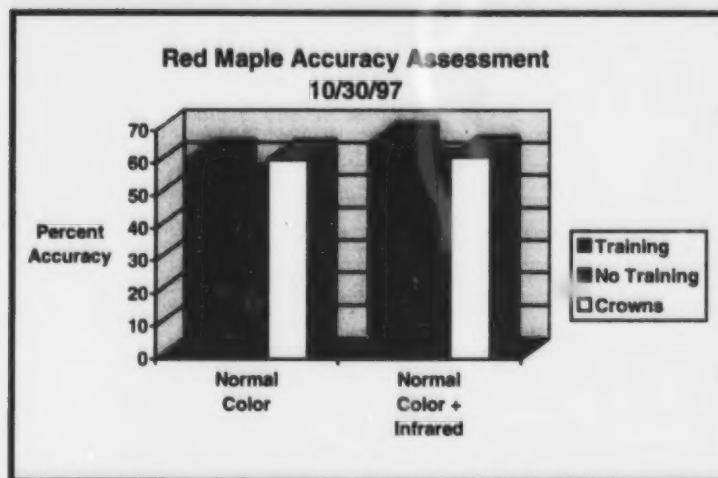


Figure 3. Accuracy assessment for red maple. This accuracy assessment compares two different band combinations for October 30, 1997. The first combination uses three bands of normal or true color while the second classification uses the same three bands plus the infrared band. Note the overall increase in accuracy for red maple with the introduction of the infrared band.

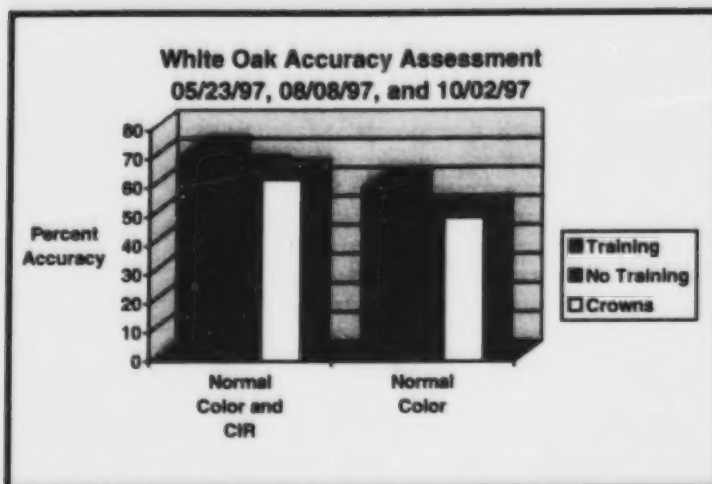


Figure 4. Accuracy assessment for white oak. This accuracy assessment compares two different multitemporal band combinations for the same dates. The first combination uses three bands of true color and three bands of CIR for each of the three dates (eighteen bands total). The second classification uses only three true color bands for each date (nine bands total). Note the increased accuracy with the introduction of the CIR bands.

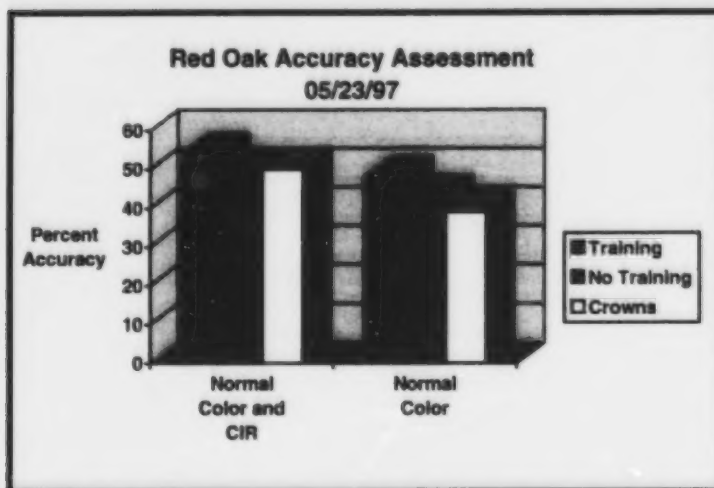


Figure 5. Accuracy assessment for red oak. This accuracy assessment compares two different band combinations for May 23, 1997. The first combination uses three bands of normal or true color plus three bands of CIR (total of six bands) while the second classification uses only the three true color bands. Note the overall increase in accuracy for red oak with the introduction of the three CIR bands.

FOREST ANALYSIS UNDER PARTLY CLOUDY CONDITIONS FOR LARGE MOSAICS OF CASI DATA

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ABSTRACT

Airborne multi-spectral (CASI) imagery has been acquired for several operational forestry project areas in BC. The imagery from separate flight lines have been mosaiced and georeferenced using TRIM digital elevation models. Analysis algorithms were developed to enable interpretation of the imagery in sunny, partly cloudy or totally cloudy situations. The output products included land classifications, crown closure and stem counts. Some of the analysis problems and techniques are discussed with example imagery showing the results. The final products include maps generated at a 1:10,000 scale according to BCGS mapsheet numbering.

RÉSUMÉ

ANALYSE FORESTIÈRE DE GRANDES MOSAÏQUES DE DONNÉES CASI CAPTÉES EN CONDITIONS D'ENNUAGEMENT PARTIEL

À l'aide d'un spectromètre imageur aéroporté compact (CASI), on a obtenu une imagerie multispectrale pour plusieurs sites de projets en foresterie opérationnelle, en Colombie-Britannique. L'imagerie captée le long de différentes lignes de vol a fait l'objet d'un mosaïquage et d'un géocodage à partir de modèles altimétriques numérique TRIM. On a créé des algorithmes d'analyse qui permettent d'interpréter les images prises en conditions d'ensoleillement et d'ennuagement partiel ou total. Les travaux ont permis de produire une classification des sols, une évaluation de la fermeture du couvert et un dénombrement des tiges. Le présent rapport traite des problèmes qui se sont présentés en cours de route et des techniques d'analyse utilisées, et il présente, à titre d'exemple, une imagerie illustrant les résultats. Parmi les produits finals, on compte des cartes réalisées à l'échelle 1/10 000 avec numérotation BCGS des feuilles de carte.

INTRODUCTION

ITRES is the developer and manufacturer of the CASI multi-spectral airborne scanner. Over the past two years, ITRES has expanded its activities into providing acquisition and analysis services using the CASI sensor. The initial area of emphasis has been forestry applications. This paper outlines some of the current capabilities of the system and the resultant products.

Much work has been done in image analysis for forestry applications. This work has usually involved multispectral data and has often included modelling of the forest canopy to assist in the identification of the crowns. This research work has usually involved data collected under ideal circumstances and has been validated with very well known and well defined test plots.

ITRES has expanded upon this previous research work and has moved to an operational perspective. The sections below outline the criteria adopted for this operational stage. Then some practical problems related to mosaic generation and conifer identification are discussed. Finally, there are some examples of the output products for land cover assessments, crown closure and stem counting.

OPERATIONAL PERSPECTIVE

ITRES has adopted several operational criteria to permit the use of CASI data in an operational and cost-effective manner.

In an operational program the project areas are typically greater than 5000 ha, rather than small test areas. Interpretation algorithms need to have more general applicability across differing look angles over multiple flight lines. The small test areas are still valuable as validation sites, but any analysis parameters derived from these sites need to have general applicability.

To be cost-effective, the system must have high utilization. This means that the aircraft cannot wait on the ground for ideal weather with clear skies; rather, it must be able to fly in partly cloudy conditions below the cloud base. Then the analysis algorithms must be able to compensate for varying illuminations in the scene. This capability has the added advantage of being able to handle topographically induced shadows and local shadowing due to the trees themselves.

The imagery from multiple flight lines must be mosaiced and georeferenced. This capability is essential for the imagery and its output products to be combined with other data sources or output to databases.

Operational programs may exist in areas with very limited access or ground truth. Hence, it is highly desirable for the georeferencing not to need local ground control points.

There must be a focus on the needs of the forest manager. How the data are to be used needs to be well understood so that the output products make sense, the accuracies are consistent with the applications and the information is in a format such that it can be integrated with other relevant data.

IMAGE ACQUISITION FOR AN OPERATIONAL PROGRAM

The CASI sensor is a push-broom type scanner that collects a line of data across the flight line. This line of data consists of 512 pixels. The incoming light is split with a slit and subsequent optics into spectral bands from about 450 nm (blue) to about 900 nm (near infrared or NIR). A spatial resolution (pixel size) of 60cm has been found to be best for forestry applications. For the current CASI system, that means that a maximum of 8 spectral bands can be selected. These bands can be of varying spectral widths and locations.

In the field, the CASI data are currently collected by flying straight flight lines at a fixed altitude for each flight line. For 60cm pixels and the current CASI optics, the distance above ground should be about 400m. If the ground is further away, then the swath width is wider and the raw pixel size is greater than 60cm in the cross-flight direction. If the ground is closer, then the swath width is narrower and some narrow slices of the ground might be missed.

A typical flight block of contiguous flight lines might involve about 10 or more individual flight lines. Then there could be about 10 or more flight blocks for a typical project area. The orientation of these flight lines may be determined by local topography or by the areas of interest. This operational constraint is significant, since in research applications, it is highly desirable to fly into or away from the sun direction to avoid serious backlighting or forelighting effects. For operational programs, all directions of flight need to be used. The impact of this constraint is discussed below in the sections on crown closure and stem counting.

PROCESSING AND THE USE OF LARGE MOSAICS

The processing involves radiometric corrections for the spectral sensitivity and the optics of the CASI sensor. Then the data are georeferenced based upon carrier-phase differential GPS and TRIM digital elevation models. The data are resampled using nearest neighbour to generate a georeferenced ortho-image mosaic. The relative alignments of the CASI and the inertial system are determined after each installation using a known test area with an accurate detailed DEM. This calculation of relative alignments means that no ground control points are needed in the operational field areas to achieve georeferencing.

The mosaic size is set to enable efficient subsequent processing for landcover, stem counts, etc, in an image analysis system. Typically, the processing mosaic is about 2000 ha for 60cm pixel sizes. These processing mosaics are later combined in a GIS system for integrated output products.

The use of large-area mosaics satisfies the operational criteria identified above, but they present some problems to overcome for analysis and interpretation.

The first problem is that the georeferencing must be sufficiently accurate, so that there are not major discrepancies between flight lines. The reference DEM is TRIM and it is accurate to about 10m, 90% of the time. Any errors in the DEM will be amplified at flight boundaries where the look angles from adjacent flight lines will be opposite. Similarly if there are inaccuracies in the GPS, these errors will be most noticeable at the boundaries between flight lines. A useful quality-assurance procedure is to overlay the TRIM road vector file on the CASI land cover analysis. The high level of coincidence between the vectors and the gravel/road spectral characterization demonstrates that the georeferencing is consistent with the TRIM accuracies.

After georeferencing is achieved, there will be sharp differences in illumination at flight line boundaries. One flight line may be in sunlight and the neighbouring line may have been flown in shadow. Hence the analysis algorithms must be sufficiently robust to handle such illumination differences. Also, the dynamic range of CASI must be sufficiently large so that information can be obtained in both deeply shadowed and brightly sunlit areas.

The third major problem to address with mosaics is the different look angle at the boundaries. The look angle makes trees lean away from the nadir. Adjacent flight lines will have trees leaning in opposite directions. This problem is partly aesthetic. If the land cover classifications and the conifer crowns can be properly identified, then the remaining problem is mostly in crown closure estimates.

DYNAMIC RANGE OF THE IMAGERY

When imagery are collected under varying illumination conditions, there must be sufficient dynamic range in the sensor (and subsequent processing) such that useful information is obtained in both brightly lit and heavily clouded areas. It is possible to vary the amount of light coming into the sensor through aperture control, but for practical operations, the sensor itself must have significant dynamic range to account for brightly lit and dark portions of the imagery.

The CASI sensor is a 12-bit system that normally provides sufficient dynamic range for typical illumination variations in operational conditions. Figure 1 is a mosaiced image of flight lines in 3-band "true" colour without any illumination corrections. The detail imagery shows the darkest area within the imagery. It is clear that there is sufficient dynamic range to permit subsequent interpretation of the dark cloud covered areas of the mosaic.

CONIFER IDENTIFICATION

The criteria that look angles and illumination differences do not impact the eventual analysis products can first be examined by the ability to generate a conifer filter that is not sensitive to these differences.

One method is to use spectral angle mapping (SAM), a standard technique used for land cover classifications. This procedure worked reasonably well if proper allowances were made for differing illuminations through a normalization technique. Since the land cover classifications are normally used for general interpretations, there can be some uncertainties in the conifer filter without any significant impact on the output land classification distributions.

For crown closure, stem counting and species/health assessments, the conifer mask needs to be more accurate. There are numerous complications to performing this function in an automated manner in typical forest stands. Compounding the illumination and look angle effects are differences associated with the variations in conifer signals due to age, local micro-site and diseases. These factors confuse the spectral signature and make species separation particularly difficult; (a sick pine looks a lot like a sick spruce).

One general illumination problem is the false identification of conifers due to effects of shadows and forward scattering. One simple technique to identify conifers is a ratio of NIR to red. (This is the same as the NDVI (normalized difference vegetation index), with a different histogram weighting). However, this simple approach leads to streakiness in the direction of the sun. This streakiness is due to shaded areas of openings returning a conifer-like signature. Light is scattered from the conifers and then reflected back by the dead vegetation in the openings resulting in a weaker signal with a conifer spectral signature. If an illumination-dependent criterion is applied for the value of the blue-green ratio, then this streakiness disappears as the shaded openings are correctly removed. The blue-green ratio is used as a marker for changed incoming illumination and the criteria for a conifer signature can be adjusted accordingly. A similar phenomenon occurs for topographically shaded areas.

CROWN CLOSURE

An initial estimate of crown closure can be made directly from the land classification analysis. If this is done, there can be increased values along the edges of the flight lines, particularly in partly open stands with larger trees. This effect is due to the identification of conifer spectrum from the side of the conifers at larger look angles. At near-nadir look angles, the openings can be seen clearly, but these openings can no longer be seen at larger look angles, particularly with tall trees.

ITRES has developed a measure to compensate for this effect in backlit situations. The backlit sides of trees have a different spectral signature and intensity compared to the crowns of the trees. A measure of the crown closure can be generated using this information. Then the absolute value of the crown closure can be "calibrated" by examining uniform stands that extend from near-nadir to larger look angles and demanding that there be minimal differences due to look angle. The results of this methodology are shown in Figure 2. In this image, there are three flight lines, two in heavily overcast conditions and the middle one in a partly cloudy condition. The removal of the illumination and look angle effects appears to be effective.

Figure 3 shows an example of one of the areas used to calibrate the crown closure filter at near nadir look angles. One concern is that the crown closure being used as the "calibration reference" is the percentage of conifer signal at near-nadir look angles. The methodology removes illumination and look angle effects, but the absolute value is based upon the total conifer coverage passing a purely spectrally based conifer mask.

When this methodology is applied to a large mosaic, there are some residual artifacts aligned along the flight lines. These artifacts arise due to the forelighting side of the conifers at large look angles. If the flight lines could be oriented away from and into the sun, then these effects are minimal. However, operationally, terrain and areas of interest often demand flight lines across the sun direction, which compounds the forelighting problem. ITRES is currently working on techniques to identify forelighting situations so that a similar adjustment can be made to the areal coverage for forelighting effects as has already been implemented for backlighting effects.

STEM COUNTING

ITRES currently uses four different techniques for stem counting depending upon the application.

For very large trees, a valley-following technique is applied. This technique is based upon work undertaken by François Gougeon and colleagues, currently at the Pacific Forestry Centre.

For very small trees in regeneration areas, the difficulty is detection of the isolated conifers themselves. This technique is discussed in a companion paper by Rob Price et al. It has been applied to many NSR areas in British Columbia. Each conifer may be subpixel in size and so the full 8 bands of spectral information are used to develop the conifer mask. Since the stem counts have to be "well spaced" for NSR applications, a well-spaced algorithm is used to eliminate conifer pixels that are too close.

For mid-size trees in medium density stands, individual stems are identified by a local maximum criterion and a conifer mask. This methodology directly detects the dominant and co-dominant trees. Validation efforts have been undertaken as part of the Justine Lake CASI Project in stands with dominant and co-dominant stem densities of up to about 2500 stems per hectare.

For mid-size trees in very dense stands, texture techniques have been applied in a neural net decision algorithm. Ground counts are used to train the algorithm. This methodology is effective in showing relative changes in the stem densities. However, the ground data show such large changes in adjacent count plots that high accuracy is probably not attainable and may not even be relevant for decision making. Again, the CASI directly detects the canopy and perhaps partly down into the canopy. Even if stocking levels are used to train the CASI data, it cannot detect changes in the understory if those changes are not reflected in the canopy or in openings visible by an airborne CASI.

Figure 4 shows stem counts calculated using a local maximum method and a conifer mask in the Justine Lake area in the Vanderhoof Forest District. The variations in stem counts appear to reflect the imagery and specific validation sites. Some linear anomalies exist along the direction of the flight lines. These are due to large backlit trees. The narrow outline of a large backlit conifer, passed by the conifer mask, may be broken up if there are large branches. In this situation each large branch can be separated and may be counted as a separate tree.

Figure 5 shows a close-up of one validation site in the Justine Lake area, where the changes in the stem densities are evident in the CASI imagery and are reflected in the stem counts. Eleven test sites were used in this test area to compare the generated and observed counts. The results indicated that there was high variability in adjacent count sites, but the CASI counts reflected the number of dominant and co-dominant trees.

HEALTH AND SPECIES ASSESSMENTS

Health and species assessments are currently underway at ITRES as part of a number of programs.

The health issues being examined include root rot (tomotosis), gall rust, dwarf mistletoe and various other stress inducers. One critical element that has emerged is the need for a very good test area where the ground truth is very well known so that the incidence and severity of the health impact can be accurately known for algorithm development and testing. The sites currently being used for root rot and gall infection are the Beaver Forest Road site and the Dog Creek site respectively. Efforts at these sites have been undertaken with the involvement of Richard Reich of Prince George Region MOF.

Species separations have been initiated in the Justine Lake CASI program. Some species separations, such as black spruce and fir are relatively easy in varying illumination conditions. However, the addition of various levels of diseases causes the spectral signatures to vary considerably, making the separation of pine and spruce more difficult. Various techniques to address this problem are under development.

Figure 6 shows an example of a severely mistletoe-infected pine stand, with some health spruce along the lakeshore.

CONCLUSIONS

This study presented an overview of some of the techniques being used to handle illumination variations and other criteria resulting from using CASI for typical forest stands in an operational setting. The operational perspective presents criteria that demand greater robustness in analysis methodologies. The results demonstrated that high resolution CASI imagery can be used to generate a variety of interpretation products within a fully georeferenced framework.

Identified areas of current work include species separation algorithms for stands with varying health/stress in conditions of varying illumination. The desired accuracies depend upon the decisions being made by foresters utilizing the data.

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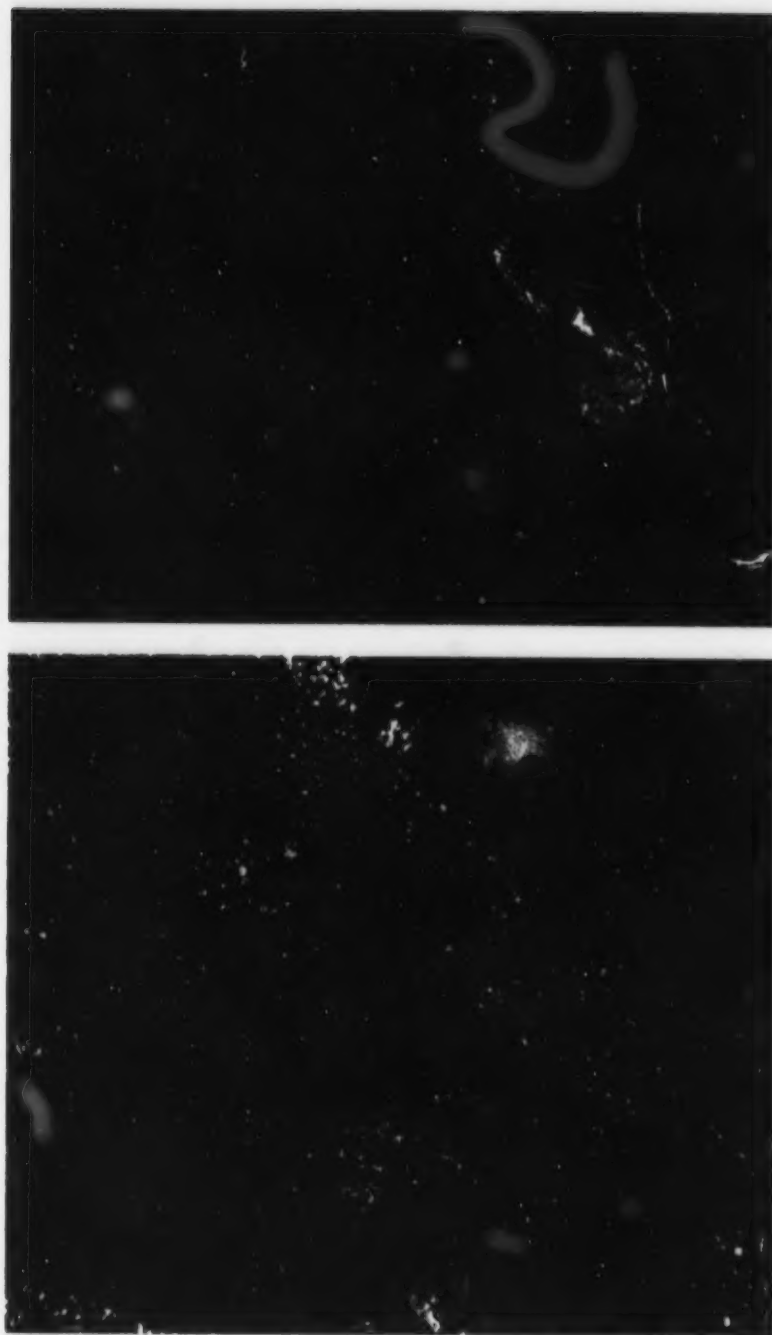


Figure 1. The top image is a true colour image of an analysis mosaic. The boxed area in the dark area of the top image is shown at a detailed scale in the lower image, demonstrating the dynamic range of the CASI imagery and the details with 60cm pixels.



Figure 2. Example of the behaviour of the crown closure conifer mask algorithm for changes in illumination and look angle for areas of fairly dense stands.

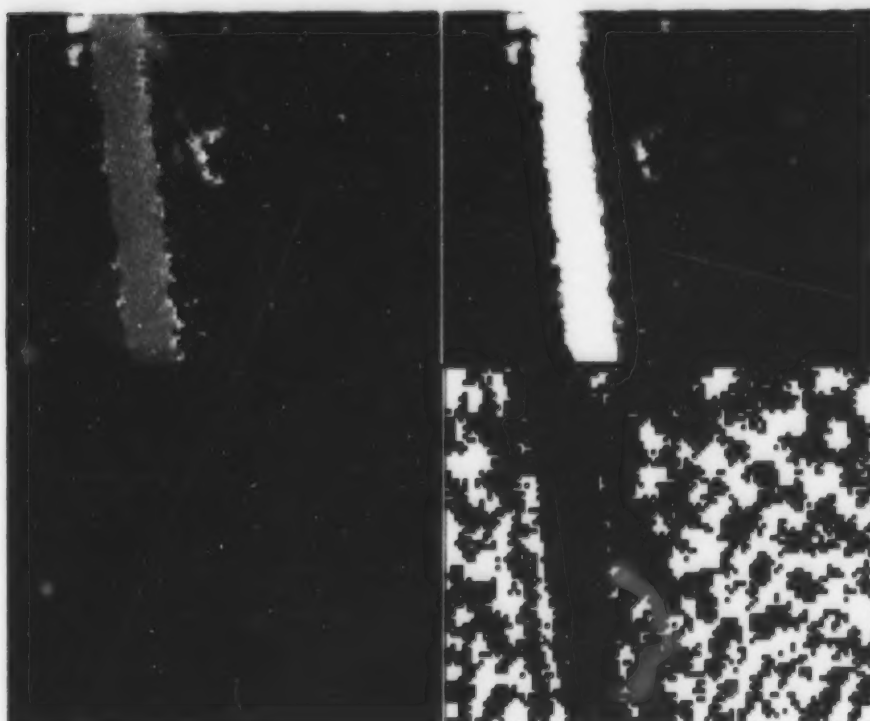


Figure 3. Example of the spectrally based conifer mask (lower right) and the crown closure mask (lower left) at near nadir with the corresponding false colour and true colour CASI images. The closure mask was largely insensitive to look angles, but its closure values appeared to underestimate actual closure values. It was calibrated using the spectrally based conifer mask at near nadir look angles as shown above.

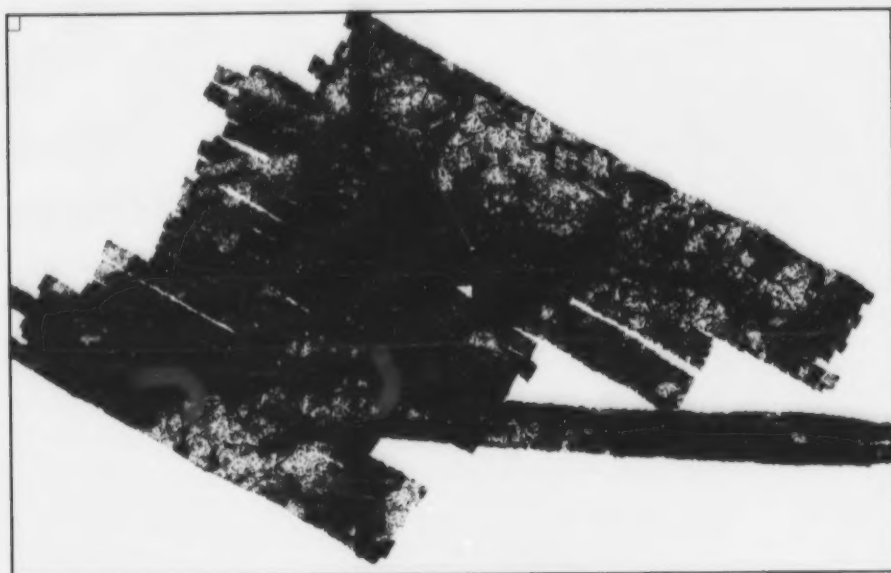


Figure 4. Stem density map of about 7000 ha of the Justine Lake Project area. The analysis algorithm measures detectable stems at canopy level, not the total stocking levels. The colour coding for stems density (stems per ha):

Black	0 (no trees)	Yellow	1200-2000
Blue	1-700	Red	2000-5000
Green	700-1200		

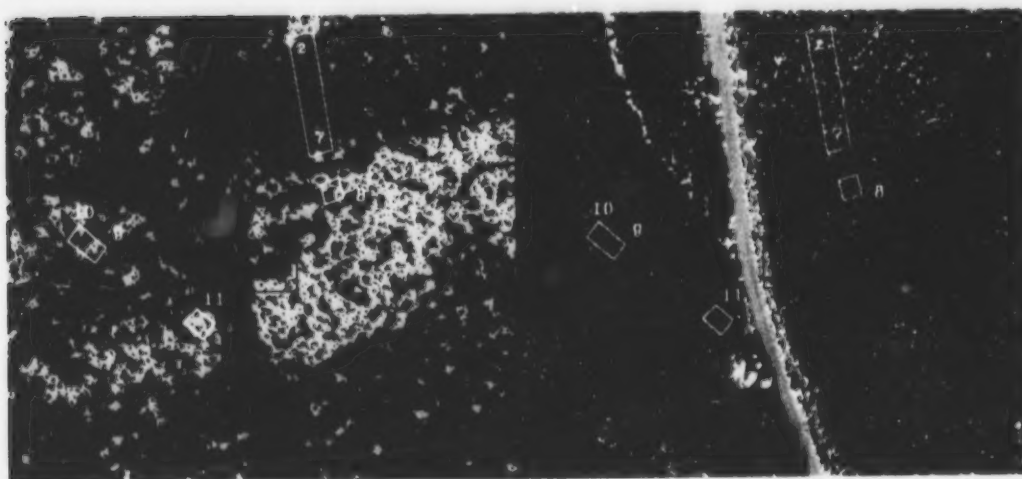


Figure 5. A detail of one of the validation test areas used for the stem counts. Eleven test plots were used at this area.

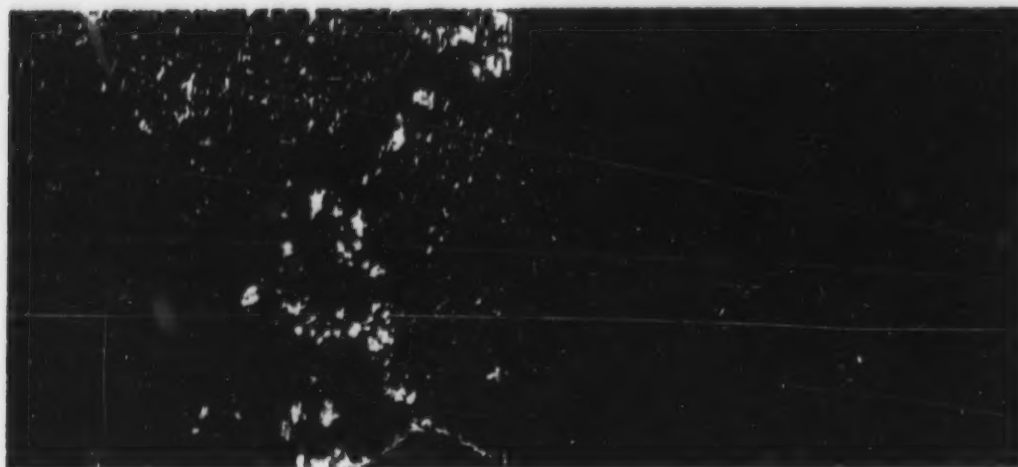


Figure 6. A test area in the Justine Lake Project showing a false colour image on the left and a normalized colour-coded NIR to red ratio on the right after application of a conifer filter. The purple areas were ground truthed as being pine with heavy mistletoe infection. The green areas were mostly larger spruce close to the lake and some small understory spruce. The colour coding used:

Green	high NIR/Red
Coral	medium NIR/Red
Purple	low NIR/Red

Stand Structure, Crown Closure and Gaps



IMAGE SPECTRAL AND SPATIAL INFORMATION IN THE ASSESSMENT OF FOREST STRUCTURAL AND BIOPHYSICAL DATA

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ABSTRACT

Remote sensing instruments generally regularize a continuous ground surface into a grid of similarly sized and shaped pixels. This regularization results in similarity of neighboring pixels which represent the same objects on the ground. The above ground organization of vegetation in a forest is considered the forest structure. At a high spatial resolution, at approximately 1m, the spatial information that is created through this discretization represents the forest structure. This image spatial information may be applied to improve the accuracy of estimates of forest biophysical and structural parameters from remotely sensed data. In this paper the relationship between image spatial structure and forest structural information is presented. To demonstrate this relationship, examples of the estimation of forest structural parameters from the spatial and spectral information collected with an airborne imaging spectrometer (CASI) at a spatial resolution of 1m are presented.

Keywords: forest structure, forest inventory, leaf area index, image spatial structure, autocorrelation, semivariance, texture, Getis statistic, clustering, digital image processing.

RÉSUMÉ

INFORMATIONS SPECTRALES ET SPATIALES D'IMAGERIE AUX FINS DE L'ÉVALUATION DES DONNÉES SUR LA STRUCTURE ET LA BIOPHYSIQUE DES FORÊTS

Les données de télédétection se rapportant à une surface continue au sol sont généralement structurées en une matrice de pixels de dimension et de forme homogènes. Cette structuration matricielle se traduit par l'obtention d'une similarité entre pixels adjacents associés aux mêmes objets au sol. L'organisation au sol de la végétation forestière constitue ce qu'on appelle la structure de cette forêt. Avec une résolution spatiale élevée, soit jusqu'à environ un mètre, l'information spatiale résultant de cette discrétisation représente la structure de la forêt et peut être utilisée pour améliorer le degré de précision des évaluations des paramètres biophysiques et structurels forestiers à partir de données de télédétection. Ce rapport fait état du lien qui existe entre la structure spatiale des images et l'information sur la structure des forêts. Pour illustrer ce lien, l'auteur présente des exemples d'évaluations des paramètres structurels réalisées à l'aide d'informations spatiales et spectrales recueillies par un spectromètre imageur aéroporté compact (CASI) à une résolution spatiale de un mètre.

INTRODUCTION

INCLUSIVE FOREST MANAGEMENT PRACTICES

Canada contains approximately 10%, or 417.6 million hectares, of the global forest cover (Westoby, 1989). Canadian forest products account for 18% of the world's forest products exports, which in 1993 were valued at \$27 billion (NRC, 1995). Canada's forests have been estimated to contain 2.6×10^{10} tonnes of biomass and $2.4 \times 10^{10} \text{ m}^3$ of gross merchantable timber (Brand, 1990). The importance of forests, both environmentally and economically, has necessitated a change in Canadian forestry policy. The implementation of ecosystem management shifted the emphasis from maintaining the ability to harvest a known quantity yearly, based on annual allowable cut, to the maintenance of healthy, diverse ecosystems. This change in forest management policy in Canada illustrates the shift in global forest management priorities from stand management to ecosystem management (NRC, 1995). A key change resulting from this change in priorities is the monitoring of complete natural ecosystem areas, not only the artificial boundaries of a forest management area. Inventories under traditional forest stand management generally consisted of measures of age, species, and timber volume; yet within an ecosystem management framework, the level of detail of measures is increased, requiring information on soils, productivity, and habitat requirements (Wagner, 1994). Within an ecosystem management framework, the future management goals for a forest are considered in terms of age, composition, structure, distribution, and aesthetics (Gillis and Leckie, 1993), as well as non-timber values, such as potential for employment and recreation (CCFM, 1995). The techniques utilized by forest managers and forest scientists are continuing to overlap as the need for sustainable forest management increases (Toman and Ashton, 1996).

FOREST STRUCTURE FOR ECOSYSTEM MONITORING AND MANAGEMENT

Forest structure is the above ground organization of plant materials (Spurr and Barnes, 1980) with the structure of a given forest being the result of competition for light, water, and nutrients at a particular location (Kozlowski et al. 1991). Forest structure may vary from homogeneous even aged stands to heterogeneous mixed stands with multiple age classes. The greater complexity of mixed forests compared to pure forests is a reflection of the variations among species in crown form, phenology, growth rate, longevity, and size. Accordingly, the ability to assess the structure of a forest permits insight into environmental factors such as hydrology, albedo, productivity, and soils. An understanding of forest structure enables the monitoring, modeling, and prediction of important biophysical processes, such as the interaction between the forest and the atmosphere, based upon the input of a forest structural measure to a forest productivity model (Running et al. 1994). Changes in forest structure may also provide for forest inventory information related to forest vigor, harvests, burns, stocking level, disease, and insect infestations (Gillis and Leckie, 1996). As suggested, forests may be characterized in terms of inventory measures or biophysical parameters. Inventory parameters provide detailed data on the location and extent of forest resources, such as species composition, age, height, tolerance level, density, and crown closure (Gillis and Leckie, 1993).

Forest biophysical parameters provide data on the productivity, structure, and amount of forest resources. Table 1 presents and defines the most common forest biophysical parameters. These measures are most commonly used as they are often correlated to other measures, can be applied to any plant canopy and may be integrated into regional scale models (Running and Hunt, 1994). Forest biophysical parameters are often an attempt to simplify the measurement of forest structure into a single measure, such as leaf area index. LAI is an important structural attribute of forest ecosystems because of its potential to be a measure of energy, gas, and water exchanges. Maximum canopy leaf area is correlated to mean annual temperature, length of growing season, mean annual minimum air temperature, and water availability (Gholz, 1982). Further, physiological processes such as photosynthesis, transpiration, and evapotranspiration are related to LAI (Pierce and Running, 1988).

Parameter	Detail
LAI	leaf area index - is a measure of area of foliage per unit area of ground
Biomass	biomass - is the total of absolute amount of vegetation present (often considered in terms of above ground biomass)
NPP	net primary productivity - is similar to biomass, but has a temporal component as it is related to the amount of biomass accumulated over a given time period

Table 1. Typical forest biophysical parameters (definitions after Bonham, 1989).

The collection of the detailed measures that characterize a forest inventory has previously been limited by the technical capabilities of remote sensing instruments. Current technological developments are enabling greater spectral and spatial resolution on a variety of platforms enabling the remote measurement of inventory parameters (Leckie, 1990; Leckie et al. 1995). Forest assessment approaches which incorporate data from a variety of spectral and spatial resolutions are necessary to address the complexity of sustainable forest management with remotely sensed data (Wulder, 1998a).

REMOTE SENSING OF FOREST STRUCTURE

Assessment of forests within an ecosystem management framework implies both geographic and economic advantages in applying remote sensing methods to generate data on forest extent and location. Yet, often remote sensing methods fail to capture the diversity of forests necessary for management decisions (Peterson and Running, 1989). Traditional methods for the estimation of forest structural parameters from remotely sensed data are commonly limited by low spatial resolution (Nemani et al. 1993) and a reliance on spectral information (Wulder et al. 1996a) resulting in an inability to capture the complexity of the forest cover. Further, complex multi-age and multi-species forests which are prevalent in Canada are especially difficult to assess with traditional remote sensing tools and techniques. High spatial resolution remotely sensed imagery has demonstrated potential for increased accuracy in the estimation of forest structural parameters through a combination of image spatial and spectral data. Image spectral information represents the vegetative characteristics of a stand while the structural characteristics are related through spatial information. The vegetative characteristics are commonly related through vegetation indices, while the spatial information may be represented by image texture. The spatial information present in variance rich high spatial resolution imagery is related to the forest structural variability. At a high spatial resolution, the local variance indicates the organization of forest vegetation.

Figure 1 demonstrates the succession of a forest stand, initially occupied by grasses, giving way to shrubs, then trees. The tree species will grow towards a climax forest of species that are best suited for the conditions at that location. Also demonstrated in Figure 1 is the increasing complexity of both vertical and horizontal structure of the forest. The vertical structure refers to tree height distribution and the horizontal distribution pertains to stand density and spatial distribution (St-Onge and Cavayas, 1995). The grasses have minimum vertical stratification and are well represented from above, in contrast to the mature forests which all appear similar from the nadir view (Wulder et al. 1996a).

The relationship between image resolution and size of the objects of interest to the analyst is a key consideration in the analysis of remotely sensed data of forests. If a number of pixels comprise an image object of interest, the imagery is considered H-resolution (Strahler et al. 1986). Yet, within an H-resolution environment there are differences in what type of information may be extracted. If the resolution/object relationship is close, where few pixels compose an object, less forest structural information will be discernible than if 100 pixels were making up the same object. This is the approximate difference between 1m and 10cm resolution imagery. At the 1m level of resolution, when considering complex multi-age and multi-species forests, a limited number of forests structural parameters may be considered for potential estimation. Inventory parameters, such as, crown closure, stand destiny, and the biophysical parameter LAI, from a combination of image spatial and spectral information will be considered in this paper.

REMOTE MEASUREMENT OF FOREST STRUCTURAL AND BIOPHYSICAL PARAMETERS

High spatial resolution (1m) image data, collected with a 2-dimensional imaging spectrometer (CASI), will be utilized to demonstrate the estimation of forest structural and biophysical parameters. After a description of the study area, and field and image data, two examples which incorporate spatial information into the estimation of forest structural parameters are presented. The first study involves the estimation of LAI from image spectral response and texture. The second example requires an initial discussion of image spatial dependence characteristics prior to presentation of how this information is related to forest structure.

STUDY AREA DESCRIPTION

The Fundy Model Forest (FMF) is a 420,000 hectare working forest in southeast New Brunswick, Canada. The model forest is located in the Acadian forest region and is composed of a variety of broadleaf deciduous and coniferous species and includes a wide range of forest conditions (Rowe, 1972) with stand ages ranging from regeneration to old growth. The Acadian forest region is characterized by a wide variety of forest species. Coniferous tree species are predominantly jack pine (*Pinus banksiana*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*), and red spruce (*Picea rubens*). The predominant deciduous species are red maple (*Acer rubrum*) and white birch (*Betula papyrifera*), with stands also including beech (*Fagus grandifolia*), striped maple (*Acer pensylvanicum*), trembling aspen (*Populus tremuloides*), long tooth aspen (*Populus grandidentata*), and sugar maple (*Acer saccharum*) (Wulder, 1996). The study area was centered near Sussex at 45° 43' North and 65° 31' West, with data collected immediately north and south of the town site. Stands were selected for inclusion in the study to represent a range of forest types, crown closures, stand densities, tree species, and LAI values.

Ground Survey Data

The ground reference data is the result of a combination of a summary survey, which collected a minimum of parameters of every tree in the sample plot, with an intensive survey that measured a selection of trees in detail (Table 2). A random sampling technique was utilized to select trees for the intensive survey within the 20 X 20m plot. For each tree in the summary survey, the diameter at breast height (DBH, 1.37m) was measured, the species noted, an identification number given, and location within the plot were recorded. Bivariate regression relationships are generated between DBH and the intensively surveyed parameters which allowed for extrapolation of all characteristics of interest to all trees in the summary sample.

plot number
slope
aspect
stand type
date
tree number
species
diameter at breast height (DBH)
location 1 (X)
location 2 (Y)
crown class (C.C.) (C = co-dominant, I = intermediate, S = suppressed, D = dominant)
sapwood width
bark width
total height
base to live crown
crown width one (with flight line)
crown width two (perpendicular to flight line)

Table 2. Ground reference data included in the intensive sample of each plot.

Based upon the plot information generated from the field data, plot maps were created. The plot maps have been degraded to a 1m grid to allow for comparison to the 1m spatial resolution remotely sensed data. The plot maps are created from the field data held in a GIS. To generate the field plot maps, information relating to tree height, canopy size, and canopy layer are included. To enable consistent integration of the plot information a C program was written.

Remotely Sensed Image Data

On July 31, 1995, at 13:00 local time, compact airborne spectrographic imager (CASI) imagery was acquired from a Cessna 310 aircraft at an elevation of 700 m and at a speed of approximately 55 knots utilizing the standard CASI 12.5 mm focal length (Anger et al. 1996). This configuration was selected to scan 1 X 1m resolution imagery with five user selected spectral bands (Table 3), to characterize significant locations on a vegetation spectral response curve. The azimuth of the data acquisition flight lines were approximately towards the sun to reduce changing illumination conditions and view angle effects. The sky was clear and the relative humidity was low, reducing the effects of the atmosphere on the imagery (Wulder et al. 1996b).

Channel and Spectral Location	Bandwidth(nm)	Centre (nm)	Width (nm)
channel 1 (green)	560.5 to 569.4	565.0	8.9
channel 2 (red)	640.9 to 649.8	645.4	8.9
channel 3 (red well)	660.6 to 669.6	665.1	9.0
channel 4 (red edge)	707.4 to 714.6	711.0	7.2
channel 5 (infrared)	748.8 to 752.4	750.6	3.6

Table 3. Fundy Model Forest CASI imagery spectral wavelength channel summary.

An atmospheric correction of the image data was undertaken utilizing the pseudo-invariant feature (PIF) calibration method outlined by Freemantle *et al.* (1992). Spectral information was recorded in the field concurrent with the CASI overflight to enable atmospheric correction of the CASI data. Paved roads, which intersect the flight lines at a number of known locations, were used as PIF targets. Image preprocessing of the CASI data is performed to radiometrically correct the data for the effects of scattered light, to remove instrument offsets, and to convert the digital numbers to standard radiometric units. An initial bundle adjustment was undertaken to correct for the non-systematic airborne imaging effects of roll, pitch, and yaw. Collection of global positioning system (GPS) ground data and flight locational data enabled differential correction and geometric adjustment of the airborne imagery. The aircraft position and angular orientation was recorded for each scanline using the onboard GPS receiver and a two-axis vertical gyro. The geometric correction process utilized this aircraft attitude information and placed each pixel of the image on a georeferenced UTM grid (Cosandier et al. 1992). The base station GPS receiver unit, located at a known geographic point, was used to correct the imagery acquired by the airborne GPS unit. For this study locational data were collected with a L1 Carrier Phase Novatel GPS receiver units at a 5 second epoch rate.

INTEGRATION OF TEXTURE AND VEGETATION INDICES FOR THE ESTIMATION OF LAI

The ability to estimate LAI from spectral response is strong up to an LAI of approximately 3 (Gong et al. 1992), after which an asymptote is normally encountered (Wulder et al. 1996a). The flattening of the relationship is due to the inability of NDVI, generated from a nadir remote sensing instrument, to sense increases in foliage overlap (Baret and Guyot, 1991) as forest complexity increases. As a result, additional information is required which still undergoes change as the forest increases in complexity. Forest spatial structure varies through levels of forest development (Waring and Schlesinger, 1985). Image spatial information may capture some of the variability in forest structure (St-Onge and Cavayas, 1997). Digital image processing provides spatial measures which characterize the spatial neighborhood of a pixel, such as, digital image texture (Wulder et al. 1998) and image semivariance (Cohen et al. 1990; Franklin and McDermid, 1993) capture information relating to the variability around a pixel related to the forest structure.

Example Estimation of LAI from NDVI and Texture

Texture has been demonstrated to be valuable in the statistical estimation of LAI (Wulder et al. 1996a). Yet, many texture measures are limited by subjective user based decisions, such as the texture measure to apply and the size of window. In this example, digital image semivariance is computed to assess the mean spatial dependence within image sample plots to dictate customized window sizes (Franklin et al. 1996) for the derivation of first and second order texture measures. First-order texture is a representative statistical value for the central cell of a fixed moving window which is passed over the image (Jensen, 1986). Second order texture measures are not computed directly from the image values but rather from the statistical distribution of local properties in the spatial domain. An example is the calculation of second order statistics from pixel relationships stored in a grey level co-occurrence matrix (Haralick et al. 1973). A hybrid spatial measure is also presented in this example, semivariance moment texture, or SMT (Wulder et al. 1998). SMT is derived from the semivariance response found at each pixel. At each pixel semivariance response is computed and significant locations of the semivariance response are utilized as spatial descriptors. The nugget, sill, range, mean semivariance between nugget and sill, and the slope of the semivariance response between nugget and sill, are the values which may be derived for each pixel with SMT.

The work of Wulder *et al.* (1996, 1998) is an exploration of the relationship between LAI, NDVI, and texture. A summary of the findings of Wulder *et al.* (1998) demonstrates the potential of a variety of texture measures in the estimation of LAI from airborne spectrometer data. The relationship between LAI and NDVI is important to provide the vegetative characteristics of a stand. The relationship between LAI and NDVI is weak when considered over a variety of stands simultaneously, due to spectral variation between stands. Within stands, the species heterogeneity will also diminish the relationship with LAI and decrease the strength of the relationships. The spectral and structural variability between stand types dictates the need for stratification between stand types for analysis. For hardwood stands, a strong initial relationship between LAI and NDVI may be found based upon broad canopy elements and species spectral similarity. In hardwood stands, primary texture measures and SMT values are found to be best related to LAI. Primary texture measures are most successful for the estimation of homogeneous cover types. SMT measures are sensitive to the spatial characteristics of the stand such as crown closure and density and as a result are useful in the estimation of a variety of cover types. Multivariate estimation of LAI from NDVI and two texture measures resulted in an increase of coefficient of variation to 0.61 from an initial 0.42 between LAI and NDVI. An assessment of softwood plots demonstrated the need for stratification between regeneration regimes. In plantations the tree planting pattern results in a strong textural component to the softwood stands. Mixed wood plots, containing both deciduous and coniferous species, consequently contain spectral variability based upon both species and vegetation distribution. As a result, texture proved significant in increasing the ability to estimate mixed forest LAI.

Based upon these encouraging results, further investigation of image spatial information in the estimation of forest structure will be pursued. Some conclusion which may be drawn from these previous studies are:

- first- and second-order texture are capturing different information based upon factors such as species spectral response and density,
- SMT is generating data related to the distribution of vegetative elements of a stand and the spectral response of these elements, and
- the performance of the texture measures in the predictive equations of LAI is found to be dependent upon forest cover type. Accordingly, in the spectral estimation of LAI, a specific texture measure may be required as input on a species specific basis.

OBJECT CLUSTERING FROM SPATIAL INFORMATION

The previous section related the increase in model variance which may be explained when estimating the forest biophysical structure variable LAI with the incorporation of image spatial information. The SMT values demonstrated the ability of semivariance to generate unique spatial information from the image spectral values. The image spatial dependence, as measured with semivariance, is a mean difference between pixels computed over a distance (Jupp et al. 1988). Semivariance computation results may provide an image analyst with an indication of the distance in which pixels are found to be similar from the semivariance range value (Bowers et

al. 1994). Knowledge of the strength of spatial dependency and the magnitude of the values within the range of the semivariogram may provide unique local spatial information relating to forest structure.

Getis Statistic

Remotely sensed imagery of forest landcover is a discretization of a continuous natural surface into a grid of regularly sized and shaped pixels. Low resolution imagery when regularized is a variance reduced representation of the surface due to the inclusion of a variety of surface cover types within each pixel. Airborne remote sensing, and the proposed high resolution satellite instruments, partition the surface into smaller pixels and, as a result, enable a representation of the surface that is capturing a greater amount of the original variance. The high resolution environment enables elements of the surface cover to be composed of more than one pixel, an H-resolution environment (Strahler et al. 1986). For example, high resolution imagery of a forest will be composed of contiguous pixel regions which represent individual trees or groups of trees. Tree objects may be understood as regions of marked spatial autocorrelation. The ability to extract information from the spatial relationships found between pixels is an appropriate complement to the more commonly extracted spectral information, such as image texture and semivariance.

Traditional methods of spatial autocorrelation are global in nature and generate values which indicate the degree of spatial association of the entire image (Goodchild, 1986). However, such approaches yield a single summary measure which may be unrepresentative if the nature and extent of spatial autocorrelation varies significantly over the image. To overcome these limitations, local indicators of spatial association (LISA) have been developed (Anselin, 1995). In contrast to existing methods, LISA measures focus on local variations *within* patterns of spatial dependence. Thus, they have the potential to uncover discrete spatial regimes which might be overlooked by existing techniques. Measures of spatial dependence, such as semivariograms, have proven valuable in digital image processing of remotely sensed imagery. Local indicators of spatial association are complementary to semivariograms while also providing some information not detectable in semivariogram analysis which allows for an improved understanding of image spatial structure. Knowledge of the magnitude of autocorrelated values is additional information available through the digital image processing of remotely sensed imagery. LISA statistics, specifically the Getis statistic, provide information based on the spatial structure of digital images. The ability to assess the strength of interpixel relationships, as well as the magnitude of the autocorrelated data, may prove valuable when the values computed from semivariance, as a positive valued function, prove inadequate for a particular objective. Measures of spatial dependence, such as the Getis statistic (G_i^*), may be modified to relate the degree of association found between pixels in remotely sensed imagery (Wulder and Boots, 1998a). Getis statistic results relate the strength of the inter-pixel relationships and the magnitude of the values found to be clustered. The intent of this section is to provide for a brief introduction of the Getis statistic and to demonstrate how it may be applied to aid in the interpretation of high spatial resolution imagery of forests.

The suite of G statistics were initially developed by Getis and Ord (Getis and Ord, 1992; Ord and Getis, 1995). Although these statistics were initially developed for the analysis of point data, Getis (1994) has demonstrated their potential to identify significant spatial dependency in remotely sensed imagery. One Getis statistic, G_i^* , yields a standardized value which indicates both the degree of autocorrelation in the values of the digital numbers centered on a given pixel and the magnitude of these values in relation to those of the entire image. Wulder and Boots (1998b) have applied G_i^* in the assessment of a Landsat Thematic Mapper (TM) image of a managed forest region. Study results indicate a strong Landsat TM channel and cover type dependence to local spatial autocorrelation measured by the G_i^* .

In general, LISA measures evaluate the extent and nature of concentration in the values of a variable x in a local region within the study area. The Getis statistics achieve this by expressing the sum of the weighted variate values within a specified distance of a particular observation i as a proportion of the sum of the variate values for the entire study area. This value can be compared with the statistic's expected value under an hypothesis of no local spatial autocorrelation to indicate if the degree of clustering of x values in the vicinity of i is greater or less than chance would dictate (Getis, 1994). Ord and Getis (1995) provide steps to derive a standardized version of G_i^* . A complete description of the derivation of G_i^* for applications in remote sensing may be found in Wulder and Boots (1998a). First global mean and variance values are computed for the entire

image allowing for computation of a standardized version of G_i^* for processing at each pixel with the following equation,

$$G_i^*(d) = \frac{\sum w_i(d)x_i - W_i^* \bar{x}}{s[W_i^*(n - W_i^*) / (n - 1)]^{1/2}} \quad (1)$$

where $W_i^* = \sum w_i(d)$, which generates results in a Z-score standardized form. Significant positive values indicate clustering of high variate values while significant negative values indicate clustering of low variate values. In consideration of remotely sensed imagery, the G_i^* values measure the extent to which a pixel is surrounded by a cluster of high or low values of a particular variable, such as image digital number (DN) values. Large positive G_i^* values denote a cluster of high DN values; large negative G_i^* values denote a cluster of low DN values. In addition, computing G_i^* within a series of increasing windows and noting the distance at which the largest G_i^* value occurs allows for an assessment of the size of the region of association around an individual pixel. A small window size (distance) indicates that spatial dependency is confined to a very localized region while a large distance value indicates more spatially extensive spatial dependence. A weakness of the G_i^* statistic, which it shares with other LISA measures (Tiefelsdorf and Boots, 1997), is that it cannot be used to identify clustering of medium values since mid-range values of G_i^* (i.e., values around zero) can result from either this situation or an absence of clustering of similar variate values.

The spatial dependency information computed with remotely sensed imagery is based upon the synthesis of image spatial resolution with the size of the objects of interest. In the case of forest inventory trees are the objects of interest. The size of the tree crown in relation to the image resolution dictates the type of spatial dependency information which will be generated. At a high spatial resolution ($\geq 10\text{cm}$), the spatial dependency information computed with G_i^* may relate the within crown spectral variability. As image resolution decreases ($\approx 1\text{m}$), the pixel spatial dependency will be sensitive to the spectral differences between tree crowns, understory, and shadow spectral components. Tree crowns are complex spectrally due to forest architectural and structural considerations, such as within crown variation in reflectance, irregular shading patterns, and tree overlap. This results in an effective resolution less than what the instrument collects, which relates the need for image data collected at a resolution finer than the objects of interest (Hyppanen, 1997). The following examples will utilize image data of 1m spatial resolution in a simulated panchromatic wavelength to simulate the specifications of proposed satellite sensors (Aplin et al. 1997) to estimate the stand density and crown closure. To illustrate the potential of image spatial dependence data in the estimation of LAI, 1m spatial resolution multispectral data is used.

Spatial Dependency within Semivariance Range

A variogram describes the magnitude, spatial scale, and general form of the variation in a given set of data (Matheron, 1963). Semivariograms are a graphical representation of spatial variability and provide a means of measuring the spatial dependency of continuously-varying phenomenon (Curran, 1988). The semivariogram also displays the average change of a property with increasing lag, although the true variogram is continuous (Oliver et al. 1989). Semivariance is the variance per site when sites are considered as profiles or areas of pixels and is developed from the theory of regionalized variables (Curran, 1988). Image semivariance has been used extensively in the assessment of L-resolution forest structure (see Bowers et al. 1994; Cohen et al. 1990 for examples; Ramstein and Raffy, 1989 for the theory). In analysis of H-resolution data, image semivariance has been demonstrated to capture image structural information (Franklin and McDermid, 1993). St-Onge and Cavayas have utilized the information inherent in the directional variogram as a method to estimate the stocking and height of forest stands (1995) and in the automated delineation of forest stands (1997).

In the near future, $\approx 1\text{m}$ spatial resolution panchromatic (450-900nm) data may be available from the proposed high spatial resolution satellite sensor QuickBird (Aplin et al. 1997). To explore the forestry potential of such imagery, 1m panchromatic data collected with the CASI is assessed in this study. The panchromatic image data was processed to generate an image of semivariance range values. Semivariance was computed in Rook's case, 4 directions, for each pixel with the results averaged to represent the pixel (Woodcock et al. 1988).

Figures 2a-d numerically illustrate the spatial dependence characteristics of a subset of CASI panchromatic image data. The central number outlined is the pixel of reference for this example. The initial panchromatic digital numbers (Figure 2a) represent a cluster of four deciduous trees, two of which have canopy radii in excess of 3m. The semivariance range values, denoted in bold in the four computation directions, illustrate the pixels which resulted in a range value of 4 to result for the pixel of interest (Figure 2b). The strength of the relationship between neighboring pixels, within the range of 4 computed with semivariance, is illustrated in Figure 2c. As noted in Figure 2d, this G_i^* value was found to be at a maximum at a distance of one. The 3X3 window in which the G_i^* was found to be at maximum is also noted in bold type. The local spatial dependency is found to be at a maximum at the central point of the cluster. The high level of autocorrelation between the pixels within the tree cluster is demonstrated by the low distance values in which the G_i^* value is maximized. The complementary nature between the semivariance generated range and G_i^* allows for the extraction of image information that increases the utility of semivariance measures. Elsewhere in the illustration high distance values are seen to relate to regions of transition. The relationship between spectral transitions and the nature of the pattern of distances at which G_i^* is maximized relates well to stand density. To enable comparison, Figure 3a-d graphically illustrates the spatial dependence characteristics of the same image subset used for demonstration in Figure 2a-d. With 1m spatial resolution, as stand density increases, the amount of change of distance values within an area also increases. Segmentation of Getis statistic values is relatively straightforward as each pixel is a value which relates its association to its neighbors. From local minimum and maximum seed points, clusters are grown based upon group inclusion through minimum difference between pixels.

SPATIALLY CLUSTERED OBJECTS IN THE ESTIMATION OF INVENTORY PARAMETERS

In Wulder (1998b), the spatial dependence information of 1m panchromatic and multispectral CASI imagery are investigated for properties which may allow for estimation of forest structural parameters. The following is a summary of that work utilizing 1m spatial resolution panchromatic data to estimate the forest inventory parameters of crown closure and stand density. Estimation of the forest biophysical parameter of LAI is enhanced through the incorporation of image clusters representing large individual trees or groups of smaller trees.

The sample plots for this study are within complex stands of variable density, closure, species, and productivity. When considering the spatial dependence characteristics of remotely sensed imagery the relationship between the objects of interest and resolution is of prime importance. Very high spatial resolution data, when processed for spatial dependency clusters, generate data relating to characteristics such as branch level clustering and distribution of foliage at the individual tree crown level. While at a spatial resolution of ≈ 1 m, spatial dependency data is generated which relates the presence of tree objects. Further decreases in spatial resolution result in the generation of clusters which relate the variability between stands of trees.

Measurement of the forest inventory parameter of crown closure with spatial dependency information shows promise, with image estimates of crown closure normally within 10% of field estimates. The field estimates of crown closure are based upon the areal contribution of clusters generated from clusters of high panchromatic values compared to field collected data.

Estimation of stand density may be made from multiple sources generated from the Getis statistic spatial dependency data. The actual Getis statistic values may be utilized to isolate stems, the maximum positive Getis statistic value normally relates a cluster centroid. If the tree is large, the stem may be isolated, yet if the cluster has been generated from the spectral response related to a group of trees, the cluster centroid will represent a group of trees. Density is not a measure that is well characterized by cluster information, as a variable number of trees may compose a cluster in a given instance. Relative indications of density may be discerned from the local rates of transitions between Getis distance values, while absolute measurement is problematic. In contrast to the complex image data used in this study, a simulation study with image elements of known size and distribution would be a means to decipher the effective resolution at which trees, or other objects, may be discerned.

ENHANCED LAI ESTIMATION WITH GETIS CLUSTERS

As described above, in the summary of the work by Wulder *et al.* (1996, 1998), spatial information was incorporated into empirical models for the estimation of LAI with promising results. One problem with the empirical estimation of LAI from image spectral and spatial values is the selection of pixels from which to extract the reflectance information. In Wulder (1998b), image spatial information is utilized to generate clusters (from NIR image data) which represent regions of foliage presence in a forest stand. Generation of these clusters allows for an increase in the likelihood that the pixels selected for incorporation in the empirical estimation of LAI are indeed the foliage unit suspected. Image spectral response in the clusters is compared to field collected spectral information which allows for a broad image object classification into general cover classes, such as deciduous, coniferous, and mixed, for inclusion in the computation of LAI. The image spatial information dictates the regions from which pixels are selected for spectral data, while the textural information is collected to represent the region around the pixel, not merely within the object. This allows for the characteristics of the local region to be incorporated in the empirical estimation of LAI. Utilizing spatial information to assist in the selection of pixels for analysis has improved the accuracy of estimates of LAI over previous spectral and spatial data incorporation techniques.

CONCLUSION

Image spatial information has been demonstrated to capture forest structural information. Empirical estimates of LAI from high spatial resolution imagery are enhanced by the inclusion of texture to the estimation model. Spatial clustering, based upon image autocorrelation, has also illustrated that forest structural information may be captured in image spatial data. At the 1 m spatial resolution of this present study limitations on what may be estimated are imposed. Individual trees with a small crown radius are difficult to discern, yet may be grouped into clusters generated from the image spatial information. As a result, currently with this technique crown closure may be estimated with greater accuracy than stem density.

Tree clusters generated with the Getis statistic also show promise in the estimation of LAI. The ability to use image spatial information to assist in the selection of pixels appropriate for the extraction of spectral information improved the consistency of the empirical models through the input of systematically derived data. The inverse of this approach may be applied to estimate the extent and spectral characteristics of stand shadow fractions.

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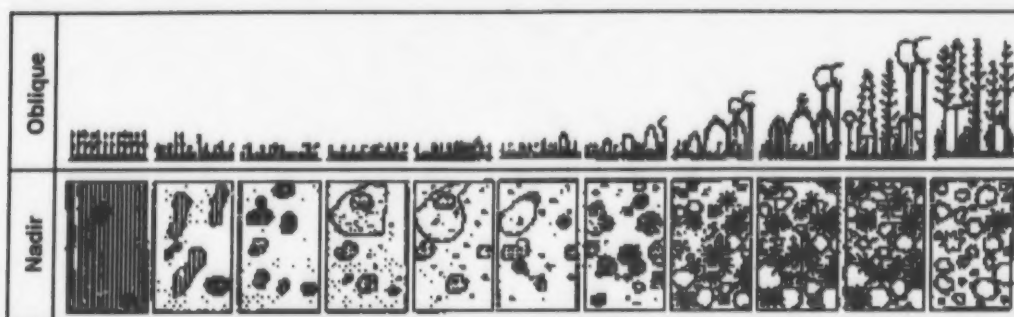


Figure 1. Demonstration of vegetation succession with increasing horizontal and vertical vegetation complexity (modified from Falinski, 1989).

38	32	29	28	28	24	26	26	25	25	25
29	27	26	29	32	27	26	28	27	26	25
27	31	32	29	30	32	29	27	26	26	24
30	34	34	30	30	34	27	24	25	27	28
26	33	34	35	33	36	34	34	33	32	36
24	28	34	35	37	37	37	36	37	32	32
26	28	29	31	36	35	33	34	36	28	33
32	25	23	21	29	32	31	30	34	31	29
28	24	20	20	26	28	26	29	32	30	27
21	20	19	15	19	26	27	28	31	30	29
15	11	9	6	9	18	26	29	28	24	22

Figure 2a. Sub-set of image panchromatic CASI data.

3	4	4	4	5	4	4	3	4	4	4
3	3	4	4	4	3	3	3	4	4	4
3	4	4	4	4	4	3	4	4	4	4
3	3	3	4	4	4	3	3	4	4	4
4	5	4	4	4	4	4	4	4	5	5
4	4	3	4	4	4	4	3	4	4	5
3	4	4	5	4	4	4	3	4	4	4
5	4	4	4	4	4	5	4	5	4	5
4	3	3	4	4	3	3	4	5	5	5
3	4	3	4	3	3	4	3	5	5	5
4	4	4	5	4	5	3	3	4	4	5

Figure 2b. Semivariance range values computed for each pixel using Rooks case.

1.38	1.16	1.11	0.94	0.84	0.76	0.65	0.50	0.37	0.33	0.09
0.91	0.98	1.01	0.99	0.92	0.69	0.56	0.49	0.43	0.33	0.34
0.91	0.91	1.00	1.01	0.96	0.87	0.86	0.80	0.72	0.66	0.63
0.86	1.07	1.23	1.17	1.18	1.13	1.06	0.96	0.89	0.86	0.92
0.76	1.01	1.30	1.37	1.44	1.41	1.33	1.16	1.06	1.09	1.24
0.78	0.81	1.16	1.40	1.56	1.60	1.57	1.54	1.37	1.33	1.30
0.75	0.67	0.75	0.99	1.24	1.44	1.41	1.46	1.31	1.23	1.28
0.73	0.42	0.40	0.54	0.74	1.00	1.10	1.13	1.11	1.07	1.16
0.40	0.09	-0.27	-0.20	0.15	0.54	0.73	0.89	0.99	0.96	0.82
-0.23	-0.55	-0.88	-0.89	-0.55	0.34	0.44	0.72	0.79	0.67	0.62
-0.62	-0.97	-1.38	-1.52	-1.25	-0.57	0.40	0.60	0.64	0.56	0.48

Figure 2c. Getis statistic values computed for each pixel.

1	1	2	3	4	4	4	4	1	1	1
4	2	3	3	4	1	1	1	1	1	4
4	1	2	2	1	1	4	4	4	3	3
4	1	1	2	1	1	2	2	3	2	2
4	1	1	1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	1	1
2	2	2	1	1	1	1	1	1	1	2
1	1	2	2	1	1	2	1	1	2	2
1	1	1	1	1	1	1	1	1	1	2
1	1	1	1	1	4	1	1	1	1	4
1	1	1	1	1	1	4	1	1	2	4

Figure 2d. Distance value at which Getis statistic value is maximized.

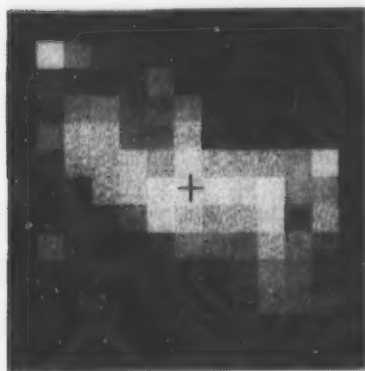


Figure 3a. Sub-set of panchromatic CASI digital image data.

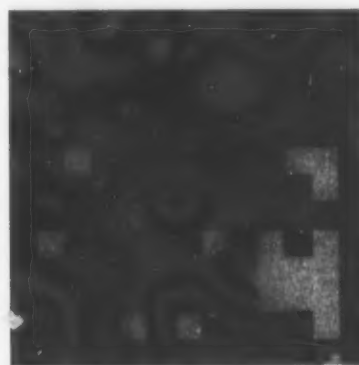


Figure 3b. Semivariance range values computed for each pixel using Rooks case.

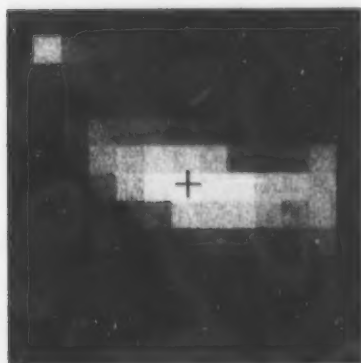


Figure 3c. Getis statistic values computed for each pixel.

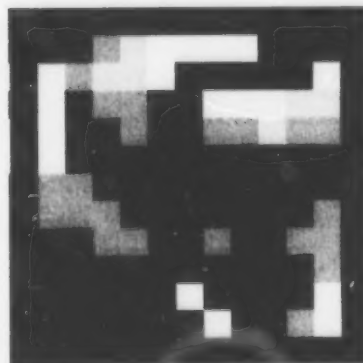


Figure 3d. Distance value at which Getis statistic value is maximized.

ON DIRECT EXTRACTION OF SCENE COMPONENT FRACTIONS AND CROWN COVER DISTRIBUTION IN OPEN FOREST CANOPIES USING HIGH SPATIAL RESOLUTION WINTER IMAGERY

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ABSTRACT

Spatial patterns of understory and overstory constitute an as-yet poorly understood obstacle to the derivation of boreal forest structural variables through remotely-sensed image data. The high resolution reflectance imagery collected seasonally as part of the Boreal Eco-system and Atmosphere Study (BOREAS) presents an opportunity to increase overall understanding of this complicated interplay. A research project is currently underway to compare and contrast two methods of separating understory from overstory in this imagery, one "directly" through classification and the other "indirectly" through end-member analysis of a high spectral resolution data set. Winter imagery is investigated to assess the best method(s) of classification into crown and snow understory. Simple thresholds are considered, followed by unsupervised and supervised classification tests by variation of scene type, tree-type, number of classes and number of wavelength channels. K-Means (Iterative Optimization) Clustering reveals that less than four classes is insufficient to effectively separate the land-cover classes for both tree-types investigated and that more than four classes leads to trivial division of existing classes. Results from this unsupervised classification are used to build training areas for Maximum-Likelihood supervised classifications. JM (Bhattacharya) distances are calculated, and it is shown that three channels provide optimum separability for both tree-types. A working methodology for winter image classification is proposed.

Keywords: CASI, classification, hierarchical, BOREAS, structural variables, understory, seasonal.

RÉSUMÉ

SEGMENTATION DIRECTE DE COMPOSANTES IMAGE ET RÉPARTITION DU COUVERT DANS LES FORÊTS CLAIRES À L'AIDE D'IMAGES À HAUTE RÉOLUTION SPATIALE PRISES EN HIVER

On ne saisit pas encore assez bien les subtilités des profils spatiaux des étages dominants et des sous-étages pour dériver efficacement les variables structurelles des forêts boréales à partir de données d'images de télédétection. Les images de réflectance à haute résolution spatiale, captées sur une base saisonnière dans le cadre de l'Étude de l'atmosphère et des écosystèmes boréaux (BOREAS) permettent de mieux cerner cette interaction complexe. Un projet de recherche présentement en cours vise à comparer et à opposer deux méthodes de séparation des sous-étages des étages dominants apparaissant sur ces images. La première méthode, dite de séparation directe, s'appuie sur la classification, tandis que l'autre méthode, dite de séparation indirecte, repose sur l'analyse par les utilisateurs d'ensembles de données à haute résolution spectrale. Des images prises en hiver sont examinées afin de déterminer quelles sont les meilleures méthodes de classification des étages dominants et des sous-étages enneigés. On envisage d'abord des seuils simples, puis on procède à des tests de classification non dirigée et de classification dirigée en faisant varier les types de scènes, les types

d'arbres, le nombre de classes et le nombre de canaux utilisés. Le regroupement basé sur les moyennes K (optimisation itérative) démontre que l'utilisation de moins de quatre classes ne permet pas de séparer efficacement les classes de couvertures au sol pour circonscrire les deux types d'arbres à l'étude. En revanche, l'utilisation de plus de quatre classes entraîne une division sans grand intérêt des classes existantes. À partir des résultats de la classification non dirigée, on établit des zones d'entraînement aux fins de la classification dirigée par maximum de vraisemblance. Les distances JM (Bhattacharya) sont calculées et il est démontré que l'utilisation de trois canaux optimise la séparabilité des deux types d'arbres. Les auteurs proposent une méthode de travail pour la classification des images prises en hiver.

INTRODUCTION

BOREAS AND ITS CHALLENGES

The Boreal Ecosystem and Atmosphere Study (BOREAS) is a multi-disciplinary project whose main objective is to arrive at some quantitative understanding of the relationship between the boreal forest and its surroundings, particularly within the context of global change. In practice, it is a series of data-taking and data-analyzing campaigns, largely geared towards gas and energy exchange between various representative boreal forest sites and the surrounding atmosphere. Remote sensing, in its capacity as a tool for environmental monitoring, seems ideally suited for this purpose because of its ability to acquire data over very large areas for relatively low cost. As such it has become a large part of BOREAS as a whole, and multispectral data now exist for a vast range of spatial and temporal scales, as well as land cover type and age.

Analysis of these data has revealed that the interplay of forest understory and overstory is a complicating effect. The boreal forest understory is an amalgam of flora, litter, soil, and water, which exists as a widely-varying component of the ecosystem. This stand-dependent variation, non-negligible in both space and season, in combination with a canopy that is characterized by large gaps and a tendency to clump, represents one of the main confounding elements in the attempt to link forest structural variables to remote sensing data. Relatively poor statistical relationships between these variables (LAI, biomass, crown closure, etc.) on the stand-scale, and simple optical indices such as NDVI, bespeak the problem: we cannot seem to be able to describe a scene without understanding sub-scene inhomogeneity.

Based on the concerns outlined here, there is a requirement for detailed investigation of the spatial patterns of exposed understory within these boreal forest sites. Such a requirement breeds very specific requirements of its own, if it is to be provided through remotely-sensed data: in particular, imagery with pixels of a size able to functionally resolve scene components and conditions such that understory is spectrally distinct from overstory. Amongst the optical imaging sensors deployed at BOREAS, the CASI provides what is perhaps the only data set available to meet these requirements (Miller et al. 1995).

CASI IMAGERY

The Compact Airborne Spectrographic Imager (CASI) instrument is a pushbroom sensor built for light aircraft platform deployment, in which two dimensions, one spatial and one spectral, are built up successively and line-by-line, with the second spatial dimension being provided by the forward motion of the aircraft. The detector array may be selectively configured to alter the combinations of spectral and spatial data, one always at the expense of the other (Anger et al. 1994; Harron et al. 1992). In utilizing the spatial mode of the imager, as was done for the data set acquired for this study, the spectral data is summed into bands in the resulting array (Table 1.). This flexibility allows us to trade spectral resolution for spatial and fulfill the first of the requirements described in the previous section. Relevant details of the processing of this imagery is included in later sections along with more detailed description of the specific data set used.

RESEARCH STUDY OBJECTIVES

The issues discussed in the first section of this paper are currently being addressed by a two-part research study, which makes use of these data. In essence the study is designed to compare and contrast two methods of

mapping the spatial distribution of the understory within the BOREAS field sites: the "direct" method, by which high spatial resolution imagery is classified such that the overstory and understory are effectively separated, and the "indirect" method, by which high spectral resolution imagery is subject to end-member analysis with similar aims. The purpose of this paper is to present the preliminary results of the first, "direct" approach.

Attempts to directly separate crown from understory in a summer image would likely fail, faced with the spectral similarity of the understory and overstory. However, the existence of seasonal imagery of the same field sites suggests a lateral approach. Classification is carried out on winter images instead, where the ground is covered by a more or less ubiquitous and spectrally distinct layer of snow. Geocorrected "masks" of understory and crown are developed, and these are cross-registered with summer images such that one forest component at a time is revealed or mapped. This is only possible since both summer and winter images are independently geocorrected and have been acquired at approximately the same spatial resolution. The success or failure of this approach will be predicated largely on the quality of i) the classified winter image, and ii) the within-image, or relative accuracy of the geocorrection.

PROCEDURE

A large portion of the work in this research study centred on preparing the imagery, to the point where classification would not be impeded by confusion due to atmospheric contributions to pixel values, and where masking would be enabled through georegistration. Therefore, prior to the classification of the images, the following processing steps were taken.

Atmospheric-correction software based on the 5S (Tanré et al. 1990) algorithm, developed and validated for the BOREAS CASI deployment (O'Neill et al. 1996; 1997), was used to process the digital number data to at-ground modelled reflectance. These data were then geocorrected using the on-board GPS data and corrected for aircraft roll using the on-board gyros and ITRES geocorrection software.

Individual images, at this point, were high resolution geocorrected strips (as images were much larger in along-track direction). Geographically coincident (but offset in cross-track direction) images were then mosaicked to form large swaths of high resolution reflectance imagery, which included the BOREAS field sites and part of the surrounding forest area. Such images could now readily be scanned for representative areas in which to test classification schemes.

The development of a working classification algorithm began simply; increasingly complicated schemes were considered only until a satisfactory result was obtained. Schott (1997) points out that classification is often most successful when carried out as a hierarchy of well-considered steps, where each step makes use of its predecessor as a scheme developed directly for specific data sets and specific data products. Especially insofar as, with the resampling and processing to reflectance of our data, this is already by and large the case, a hierarchical strategy was adopted.

The particulars of such a strategy hinged on the perceived obstacles to "perfect" classification or those effects which tend to increase overlap between classes. Two in particular deserve mention. The first is due to the nature of the reflectance values ascribed to each pixel: each value in fact is an *apparent* reflectance based on modelled above-canopy illumination, the "truth" of which varies from pixel to pixel in the scene, due to the 3-D nature of the canopy. For instance, a pure sunlit snow pixel in the centre of a clear-cut area will be subject to almost complete illumination, direct and diffuse, whereas a similarly pure pixel which occurs as a sunfleck within a stand will lack in diffuse illumination. In addition, all understory pixels will derive some fraction of its illumination from scattered radiance from both the sunlit and shaded canopy overstory. These effects will lead to a false statistical distance between the two pixels, widening the distribution of the erstwhile class of sunlit snow. A more intense, and obvious, example of this effect, that of the difference between sunlit and totally shaded snow, was expected from the start to be extreme enough to result in a new statistically significant class.

The second effect which will tend to moderate the differences between classes is that of mixing. Treitz (1997) underlines the necessity for the resolution of remotely-sensed image data to conform to the natural spatial scale of the objects/processes which they exist to study. While this has been followed to its practical

limits with the present data set, the varying and often very small natural scale of the boreal forest canopy inevitably impedes this conformation to some degree. Not severe enough to subject us to some of the more serious consequences of this scaling phenomenon, it was nevertheless expected that some unknown number of spectrally mixed pixels would be present. This problem would tend to aggravate overlap between classes.

Taking into account the above considerations, a systematic investigation of various classification methods was undertaken. The process is outlined in the balance of this section.

THRESHOLDS

The fundamental *act* of classification is the choice of a threshold, before which a pixel belongs to class (a), and beyond which a pixel belongs to class (b). Further complexity in classification schemes simply involves adjusting the mathematical basis for making this choice. In the interests of simplicity, therefore, and because of the visually-obvious distinction between regions of understory (snow) and crown, the first stage of our classification study involved an attempt at manual threshold choice through histogram analysis.

In spite of the obvious and fairly-Gaussian peaks which are clearly visible in all channels' histograms, it is found that the smooth overlap between them makes threshold choice impossible. The further step of drawing out the peaks through calculation of NDVI and some further custom indices and figures of merit (which were chosen based on the spectral differences observed in sample class spectra, taken from the images themselves) was then taken, and their respective histograms studied.

UNSUPERVISED CLASSIFICATION

Uncertainty with regard to the extent to which mixed pixels and variable target illumination would degrade class separability, meant approaching further classification methods with some caution. Imposing a particular, and perhaps physically unrealistic, number of classes on some supervised classification scheme, and having limited access to well-defined training areas, will almost certainly lead to results whose quality is a) poor, and b) difficult to judge. Three issues must be resolved before a supervised classification may proceed with confidence: first, how many non-trivial (to our study) statistical classes exist, second, where are they grouped such that one may use them as training areas, and third, do these natural statistical classes correspond to the physical land-cover classes required.

To address these issues, then, the following steps took place. Two separate mosaicked images were chosen, both with 7 image channels spanning visible and NIR wavelength regions. One of the images was of the BOREAS mature jack pine site, the other of the BOREAS mature black spruce site; both images were acquired in mid-February, 1994. Each of these images was subsetting into two smaller (approximately 300 pixels square) images, the subsets corresponding to regions characterized by clearcuts and pure canopy. This was done to decrease computing time and to separate regions that could conceivably have different responses to the clustering algorithms.

A K-means Clustering algorithm (referred to as Iterative Optimization Clustering by Richards (1986)) was then applied to each of the four subset images 12 times, once for all combinations of 2, 3, and 7 channels, and 2, 3, 4, and 5 classes. The alternating band set was included to facilitate a later investigation. The algorithm is *mechanically* robust in that each pixel is peremptorily assigned a class, based on its location in brightness space with respect to a given number of migrating class means, which iterate to final stable resting points. However, K-means Clustering is a game of musical chairs where everyone gets a seat: all pixels are grouped when there are almost certainly many that shouldn't be. This drawback of the unsupervised algorithm is side-stepped, though, because as it is only a preliminary part of a larger hierarchical scheme, only selective use of its results are made.

Starting with the largest number of classes (5), the clustered images were compared with visually realistic RGB versions of their counterpart reflectance images. Each class was evaluated for its ability to separate crown and understory, and sensible limits to the number of classes were determined based on these

evaluations. Finally, geographical regions containing large numbers of each class were identified and saved as bitmap polygons for use as training areas in supervised classification trials.

SUPERVISED CLASSIFICATION

Although the unsupervised classification has delivered results which on the whole seem to convincingly separate crown from understory, the fact remains that, firstly, our algorithm is mathematically somewhat heavy-handed, and secondly, we have no quantitative measure of this separability, a measure which could, for instance, lead us to decide on the necessary number of channels to utilise.

The original plan of using the results of the unsupervised classification, both as source of preliminary information and as input for a test of the applicability of some supervised classification scheme, is therefore held on to. A maximum-likelihood classifier is investigated.

Most supervised classification routines make use of discriminant analysis, which is essentially a decision-making algorithm of the form:

$$x \in i \quad \text{if} \quad g_i(x) > g_j(x) \quad \text{for all } j$$

where x is a vector representing a pixel in terms of its position in brightness space, i and j are classes, and the g_i are the so-called discriminant functions, whose form depends on the algorithm in question, but whom can be generally said to increase as the probability of x being in class i increases. It is also generally true that the $g_i(x)$ are characterized by a surface in brightness space and that different classification algorithms are similarly distinguished by a characteristic shape of decision-surface.

The Gaussian Maximum-Likelihood Method is such an algorithm. Assuming the pixels of a certain class to distribute themselves in a normal or gaussian manner for all wavelength channels is usually reasonable (and very desirable in terms of tractability). Since in general these classes will be characterized by a mean and a set of covariances for each wavelength channel used, the overall decision-surface is that of an N -dimensional hyperellipsoid, where N is the number of channels. The combination of robustness from a physical standpoint (modelling clusters as being normally distributed), and the intrinsic malleability of this hypersurface with its N variable semi-major axes, as compared to some of the other conventional shapes of parallelepiped and hypersphere, make it the popular choice, in spite of the commensurate increase in cost in computation time. Based on these largely theoretical considerations, the Maximum-Likelihood Classification Method was selected as best for our purposes.

Proceeding with the investigation, then, a set of classifications was generated for combinations of numbers of channels and classes which correspond to the previous unsupervised set, with the overall number reduced as a result of the evaluations done on the unsupervised classification results. Also, the two image subsets which were chosen for their lack of canopy gaps were abandoned as part of the investigation, again partly because of the results of the unsupervised evaluations, but also because it became virtually impossible to isolate sufficient training area for some classes, particularly understory.

Swain (1978) recommends using at least $100N$ training pixels for each of N spectral channels. In the images containing clear-cut regions this was easily achieved for three channels (but in some cases not for seven), by importing bitmap polygons covering pure classes that had been generated on the classification map's unsupervised counterparts.

At the conclusion of the creation of these classified maps, then, we have used the natural statistical distributions of the pixels for a set of channel combinations to choose the number and general location of classes and used these results as training data for the more mathematically elegant and well-founded supervised Maximum-Likelihood method. Visually, quality is high: careful comparisons are done for all classes by "landmarking" classes and using RGB versions of the image as a means for checking that classes are self-consistent.

Finally, to supply a quantitative measure of the statistical quality of these class separations, the Jeffries-Matusita (JM) or Bhattacharya distances are calculated for all pairs of classes and all the permutations of channels and classes which were tried. The resulting numbers were used, firstly, as general indicators of absolute separability, and secondly as relative separability measures to judge the optimum number of channels to be used in the future.

FURTHER WORK

Uncertainty with respect to the extent to which mixing of pure components within pixels would interfere with the classification was a part of this investigation from the beginning. Indeed, whether the components sunlit crown and shaded crown have any physical significance at all is an unresolved problem. At very least the appropriate scale on which to define these concepts is not known: consider a supposed sunlit crown region of an scene observed on a large-scale image. Looking closer, this pure region will tend to resolve itself into a textured combination of sunlit and shaded components. The boreal forest canopy has gaps which are modeled at all scales from stand to shoot, so repeating the process by focusing on one of these new "pure" sunlit regions will have the same result. This scaling phenomenon suggests that these intuitive scene components may be impossible to unequivocally nail down experimentally.

Two further complicating factors to separability should make themselves apparent in these winter scenes. The first hinges on the diffuse illumination of pixels, by definition that component of overall illumination which has been scattered out and back in to the path to the target. Within a stand much of this scattering comes from the surrounding trees so that *the target illumination itself* is imbued with the spectral signature of vegetation and as such so are the purest of snow understory pixels when illuminated by it. These effects are clearly shown by the component spectra in Figures 6 and 7, which are generally consistent with field measurements of component spectra at one of these sites reported by Soffer et al. (1995). The second and less esoteric effect is that of understory plant species pushing up through the snow and making it's spectral presence felt.

At the outset, therefore, contingency was necessary for the situation in which an unacceptable portion of the imaged scenes were unseparable as these theoretical components. In such a case it was planned to implement a further division in the hierarchical structure of the classification, in which the areal fraction of mixed components is estimated for only these uncertain pixels, using a linear spectral unmixing algorithm.

RESULTS

THRESHOLDS

The histogram evaluation, as has already been mentioned, revealed that simple choice of thresholds for various combinations of channels of our reflectance data was not going to be possible, as the distributions shared large overlapping regions (Figure 1).

Calculation of NDVI (Figure 2) and some other spectral indices and figures of merit failed to improve the situation in any measureable way, despite the clear differences in spectral signature of pure component regions of the images (Figure 6 and Figure 7). This suggested that there is a substantial amount of mixture within pixels and that more delicate classification measures must be taken.

UNSUPERVISED CLASSIFICATION

Starting from the largest number of classes separated by the K-Means Clustering algorithm, the mature black spruce site and the mature jack pine site results were evaluated to determine whether the desired land-cover classes corresponded to the "natural" statistical clusters, or spectral classes, of each image. In the jack pine site, use of five classes resulted in one understory class, one sunlit crown class, one shaded crown class, and two further classes which were apparently variations on shaded understory. Use of four classes cut out these uncertain classes, resulting in sunlit crown, shaded crown, sunlit snow, and one shaded snow class. It is interesting to note that spectral signatures of even the pure snow classes have small but detectable red-edge,

normally associated with vegetation; presumably this is an instance of diffuse illumination by "tree-light" as described previously (Figure 6).

The mature black spruce site behaved quite differently. With five classes demanded of the clustering routine, one class of crown appeared, along with four classes of understory (one shaded snow, and three which were apparently sunlit snow). Reducing the classification to four classes, we seem to merge two of the snow classes, arriving at a crown class, a sunlit snow class, and two shaded snow classes, one of which, like the jack pine site, has a small but noticeable red-edge. Use of four classes appears to optimize land-cover class separation, i.e., beyond four we conclude that the separations are trivial to our objectives (Figure 4 and Figure 5).

SUPERVISED CLASSIFICATION

Making use of the optimum number of classes suggested by the evaluation of unsupervised classification results, and assuming that use of the above classes as training areas for supervised classification would result in a more mathematically sound classification, a further investigation to optimize the number of spectral channels took place.

JM distances were calculated for each of the classification runs. The following simplistic evaluation scheme was used:

<i>JM Distance</i>	<i>Separability</i>
0.0 - 1.0	Extremely poor
1.0 - 1.9	Poor
1.9 - 2.0	Good

Of the 7 available channels, 5 visible and 2 near-infrared, the following combinations of channels were tested:

- 5 & 6 (red & NIR)
- 1, 5 & 6 (blue, red & NIR)
- 1 - 7 (all)

In the case of the mature black spruce sites, the lowest value occurred for the separability of the two pure snow understory classes, at 1.762 for 2 channels. All pairs of classes maintained JM distances well into the "good" separability category when 3 and 7 channels were used, improving only slightly with 7.

In the case of the mature jack pine sites, lower values were recovered, even for the 3 channel case. The minimum value was for the separability of the shaded understory class and the crown classes, hovering at approximately 1.74, which is not overly surprising considering the marked understory red-edge. When 7 channels are used, these values rise to just under the "good" mark, with the other crucial class pairs of understory/sunlit crown and understory/shaded crown well above (Figure 3).

CONCLUSIONS

The first conclusion that we feel confident in is that the winter imagery has proved successful as a means for separating understory from overstory, and that this data set will be valuable as a means for mapping of these components. A result has been achieved which is of a sufficiently high quality that we may proceed, using the described process to help form a general methodology. This is in part due to the tentative quality analysis and the careful survey of possible sources of variation in separability, and in part due to the overall apparent quality of the result when inspected visually.

Using the results to create a methodology which firstly optimizes results, and which secondly is general enough to apply to different types of site and tree species is the last step in this part of the research. Some general remarks to this end:

1. The two different tree stand types behave differently statistically under similar constraints, in other words the "first" 5 natural distributions do not correspond to the same physical land-cover types. However, the optimum number of classes is the same.
2. Over the two types of stand the optimum number of channels varies between 3 and 7.
3. Clear-cut areas are indispensable in order to achieve a statistically significant number of training pixels.
4. Regardless of the vagaries of each stand type's results, crown and understory are well separated for all cases.

Finally, a word is required with respect to the use of the JM distance. It is a biased statistic, in such a way that it is impossible for a larger number of channels to result in a lower "separability"; therefore, small increases upward must be regarded with suspicion, particularly as no account is taken for the statistical thinning out of training pixels which is inherent in expanding from, say, three to seven channels (Shepherd, 1998). There does not appear to be any indication that the required ~700 pixels per training area will be available to supplement a 7 channel supervised classification, therefore, it is concluded that 3 channels will optimize separability.

The working methodology which is suggested by these results is as follows: using 3 channels (1,5,6), and 4 unknown classes, run a K-Means Clustering unsupervised classification on the current image. With the help of clearings (natural or cut), identify pure regions within these unsupervised results and import them for use in a Gaussian Maximum Likelihood Method of supervised classification. Then using the stand-dependent results above, merge the 4 classes into 2, one of crown and one of understory, and save this result as a black and white geocorrected bitmap for later masking.

Finally, natural component mixing, as well as some visible understory flora and varying illumination, are bound to have resulted in misclassification of some pixels. Should we have adjusted the threshold on the supervised classification routine to identify some of them and applied the linear spectral unmixing algorithm to these pixels? This was certainly an option, however, it was abandoned for several reasons. The results of such a classification are of course in terms of fractions of pixels, which are not explicitly beneficial to the generation of masks of *pure* understory and *pure* crown. Some reasonable threshold could have been chosen, whereby if any pixel is judged to be, say, greater than 50% understory, then it could be classed as pure; however, it was felt that the overall improvement expected would not justify the extra cost of such a step. Good JM distances and the visual survey indicate that the number of pixels for whom these effects are ruinously severe is quite low. It is concluded that satisfactory control over the possible misclassification of pixels is in hand; from the viewpoint of the whole research objective, these errors are likely to be swamped by those associated with relative geocorrection of the seasonal images.

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CASI BOREAS 1994 Winter FFC-W Bandset		
Channel #	Centre (nm)	Band Pass (nm)
1	485.6	449.6 - 521.6
2	543.2	520.4 - 566.0
3	583.3	564.9 - 601.7
4	635.9	620.1 - 651.7
5	666.4	650.6 - 682.2
6	798.9	776.6 - 821.2
7	865.2	840.0 - 890.4

Table 1. CASI multi-spectral bandset of winter 1994 imagery (Gray et al. 1997).

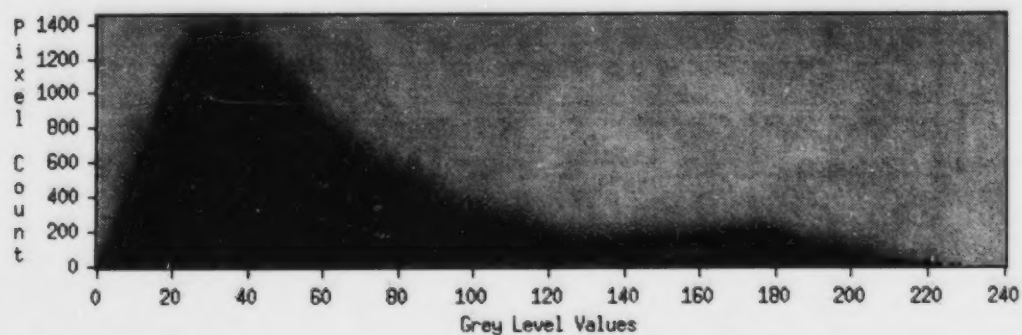


Figure 1. Histogram of NIR reflectance values for Old Black Spruce image subset.

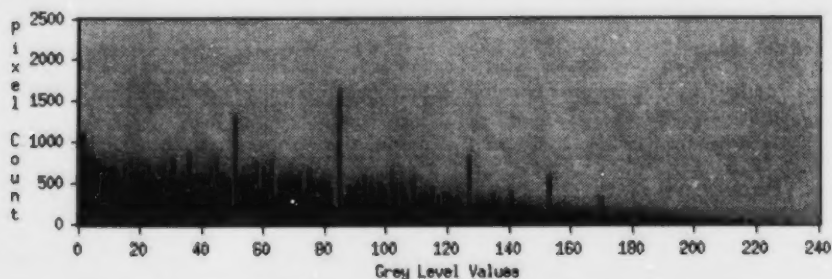


Figure 2. Histogram of NDVI values for Old Black Spruce image subset.

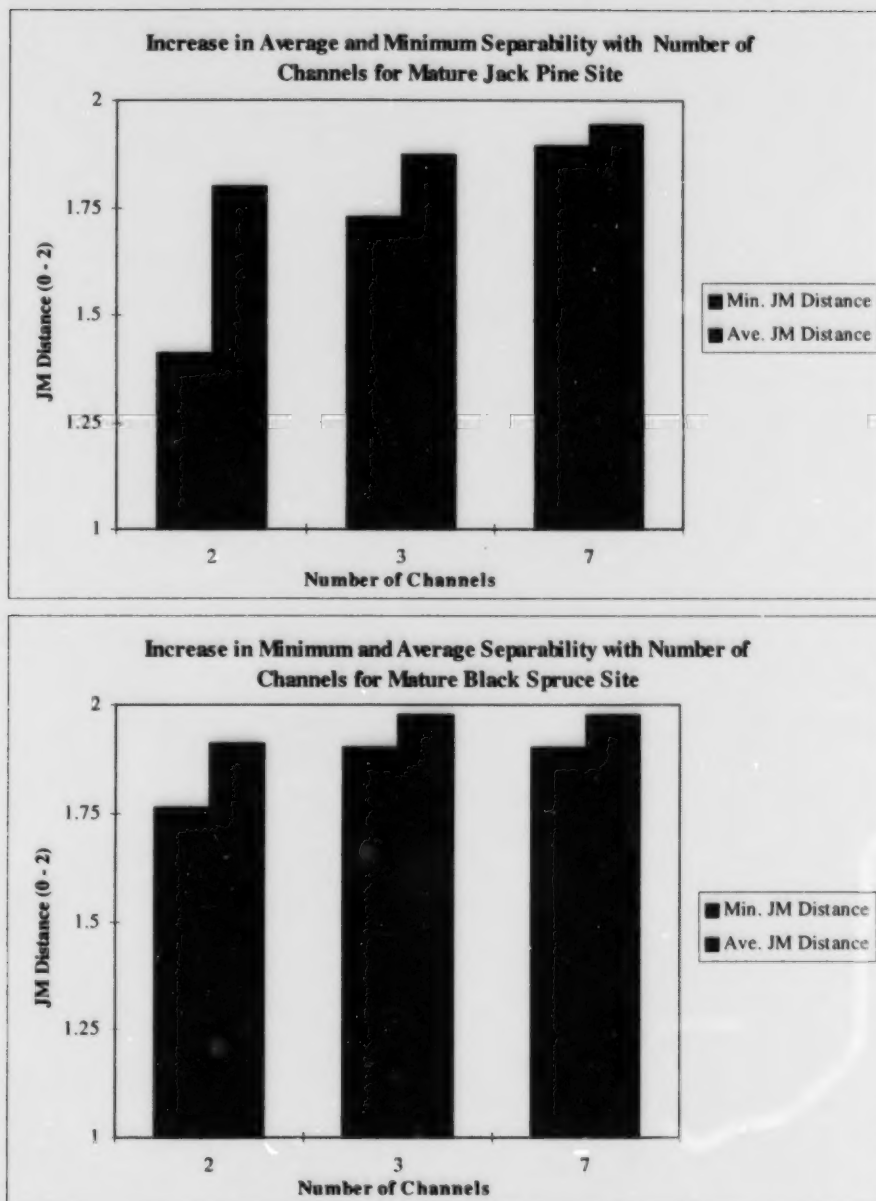


Figure 3. Jeffries-Matusita distances plotted against # of channels for Old Jack Pine and Old Black Spruce image subset supervised classification results.

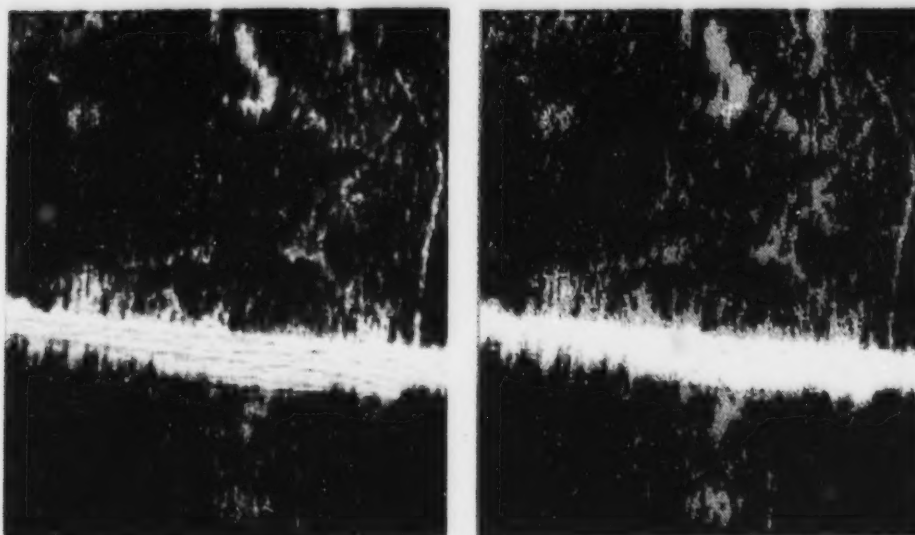


Figure 4. Comparison of NIR reflectance image (left) and 4 class, 3 channel supervised classification results (right) for Old Black Spruce image subset.

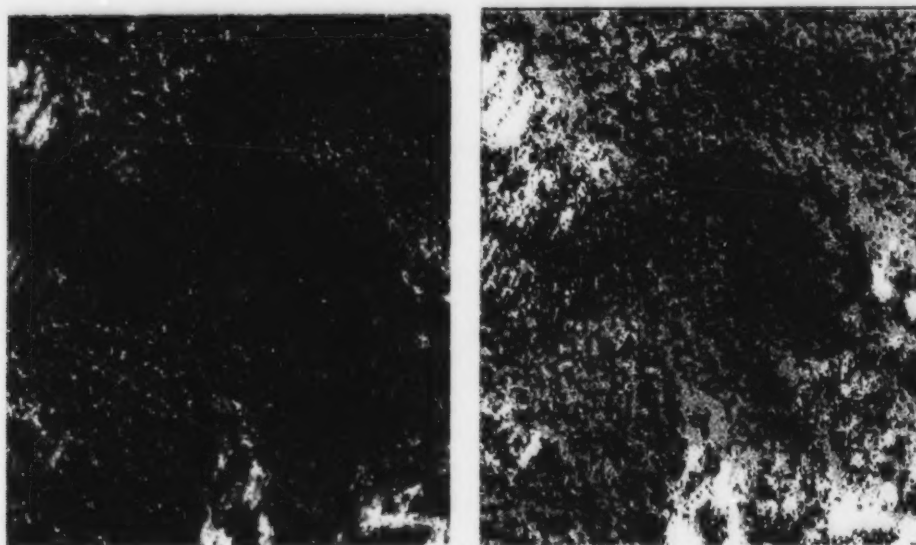


Figure 5. Comparison of NIR reflectance image (left) and 4 class, 3 channel supervised classification results (right) for Old Jack Pine image subset.

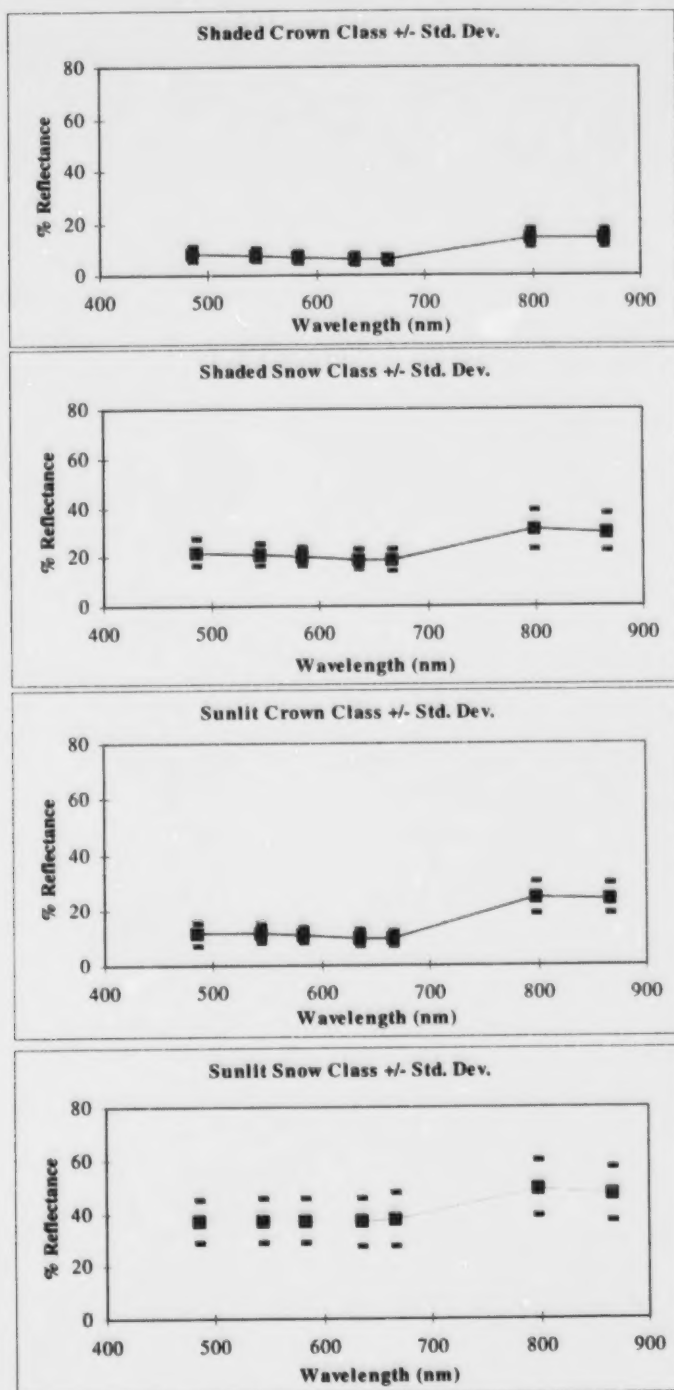


Figure 6. Class signatures for Old Jack Pine image subset derived from classification results (note red-edge in pure snow classes).

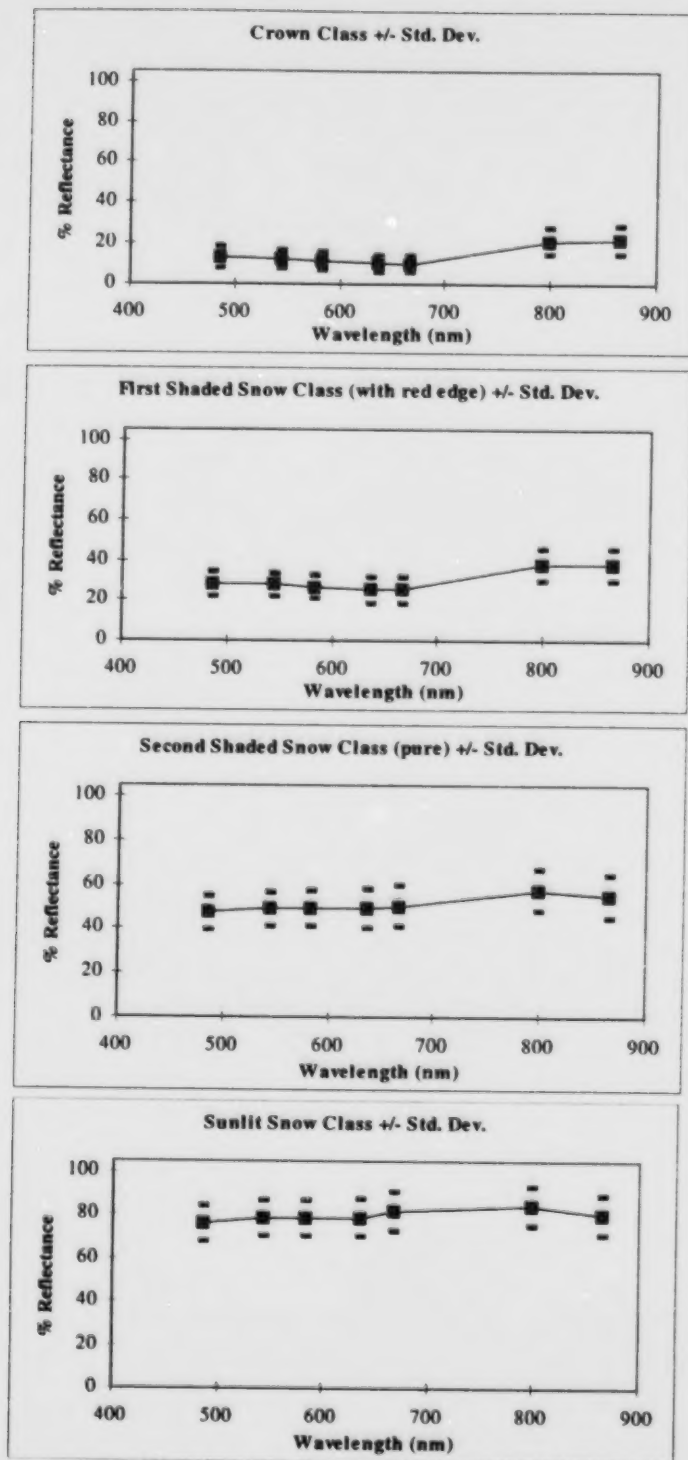


Figure 7. Class signatures for Old Black Spruce image subset derived from classification results.

OBTAINING VOLUME ESTIMATES FROM CASI IMAGES OF A THINNING AND FERTILIZATION TRIAL

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ABSTRACT

The potential for estimating per hectare values of total stem volume from CASI images (pixel size ~ 60 x 60 cm) taken over a 49 year old thinning and fertilization trial with Douglas-fir at Shawnigan Lake, Vancouver Island, British Columbia was explored. Canopy structures, stem densities and volumes varied considerably among 42 square 20m trial plots which made the site ideal for testing the assumption that volume could be predicted from a vegetation index (NDVI) and the "uniformity" of the image as portrayed through spatial autocorrelations and variances of pixel values. A combination of NDVI, variances, and coefficients of spatial autocorrelation were used as predictors of plot total stem volume per hectare. Results were encouraging, the coefficient of determination was 0.60 and the mean standard error of prediction was 10%. Wavelet analyses did not suggest any tangible improvement in the predictions.

Keywords: CASI, volume, Douglas-fir, NDVI, LAI, spatial correlation, wavelet analysis.

RÉSUMÉ

ÉVALUATION DU VOLUME LIGNEUX D'UN SITE-TEST D'ÉCLAIRCIE ET DE FERTILISATION À PARTIR D'IMAGES OBTENUES À L'AIDE DU SPECTROMÈTRE IMAGEUR AÉROPORTÉ COMPACT (CASI)

La présente étude porte sur le potentiel d'évaluation, au moyen d'images CASI (dimension des pixels ~ 60 cm x 60 cm), du volume total de tiges à l'hectare dans un site-test d'éclaircie et de fertilisation du Douglas vert exploité depuis 49 ans au lac Shawnigan sur l'Île de Vancouver, en Colombie-Britannique. Le site, découpé en 42 parcelles expérimentales carrées de 20 m présentant une grande diversité de structures de couverts forestiers, de densités et de volumes de tiges, constituait un lieu privilégié pour la vérification de l'hypothèse selon laquelle il est possible de prévoir le volume ligneux à partir d'un indice de végétation normalisé (NDVI) de même que pour la vérification de "l'uniformité" de l'image résultant d'autocorrélations spatiales et de variances des valeurs de pixels. On s'est servi d'une combinaison de NDVI, de variances et de coefficients d'autocorrélation spatiale comme prédicteurs du volume total de tiges à l'hectare dans les parcelles. Les résultats obtenus sont encourageants, puisque le coefficient de détermination a été établi à 0,60 et l'erreur-type moyenne de la prévision a été de l'ordre 10 %. Les analyses par ondelettes n'ont permis de dégager aucune amélioration tangible des prévisions.

INTRODUCTION

Estimates of the stem volume in forest stands are important to forest management for planning of harvest, thinning, and silvicultural activities (Clutter et al. 1983). Field estimates are usually derived from data of tree

height, diameter and taper collected in forest inventory plots (Hamilton and Christie 1975, Loetch and Haller 1964, Max et al. 1996). The high costs associated with volume estimation has spurred the development of efficient sample and estimation procedures (for examples, Kohl and Kushwaha 1994, Max, Schreuder, Hazard, Oswald, Teply and Alegria 1996, Schreuder and Williams 1995) and a continuous search of alternate methods based on remote sensing technologies (Congalton and Biging 1992, Dralle and Rudemo 1996, Gholz et al. 1997, Holmgren et al. 1997, Katsch and Vanlaar 1994, Naesset 1997). Two approaches appear promising. One is through classification of attributes associated with species, site type, and age, followed by a prediction of volume given the classified attributes (Brandtberg 1997, Lachowski and Bowlin 1988, Ritchie et al. 1993, Saint-Onge and Cavayas 1995, Wilson 1996, Wulder et al. 1996). The second aims at estimating a proxy of volume such as crown size, biomass, leaf area index (LAI), height, stem number, or NDVI and then the prediction of volume through simple regressions (Katsch and Vanlaar 1994, Naesset 1997, Nelson et al. 1988, Nilsson 1996). This study reports on the relationships between stem volume and NDVI and other image features obtained from Compact Airborne Spectrographic Imager (CASI) images of an intensively studied trial with Douglas-fir (*Pseudotsuga menziesii*, Mirb.) on Vancouver island.

MATERIAL AND METHODS

Field data came from the Shawnigan Lake Douglas-fir thinning and fertilization trial (Brix 1993) near Shawnigan Lake on Vancouver Island. (48°38' N, 123° 43' W). The trial was established within a fairly homogenous stand (50 ha) of mostly planted trees on a poor site (site index 25 m at age 50). Data from 42 square plots (36 from a randomized plot design with 12 treatments and three replications and six from subsidiary experiments) were used. Plot-size is 20 x 20 m. Field data reported here were collected in the winter of 94/95 when the trees were 49 years old (McWilliams and Therien 1996) and prorated, where appropriate, by one year to synchronize the field data to the laser scanner data. Prorating of heights, diameter, and volume was done via tree and trait specific relative growth rates estimated for the period between the last two measurements (McWilliams and Therien 1996). Diameter (*dbh*) was measured on all trial trees while heights (*ht*) were measured on an average of 15 trees per plot and predicted for the remaining by means of plot specific non-linear height-diameter regression models. Total stem volume (inside bark) was derived from measured *dbh*, and predicted *ht* in conjunction with local volume tables (Omule et al. 1987).

A biomass survey in 1988 and 1989 of 120 trees in 12 plots representing the range of treatments (for details see Brix 1993) provided data on needle dry weights. A total of 2214 branches were clipped, their vertical position noted, and the total needle dry weight determined after oven-drying to constant weight. A subsample of needles (~ 2 g) from the upper, middle and lower part of the crown was collected from each tree to determine specific leaf area (SLA) with a LICOR area meter. Total biomass and biomass per whorl were predicted by simple linear regressions, all with low standard errors of predictions (less than 5% on average per tree). Relationships obtained from this biomass survey were assumed to be valid for trees six years older in 1996. The vertical allocation of needle dry matter in the crown was described by a beta distribution with parameters determined from the height, diameter, and volume of a tree. Leaf area index (LAI) for each plot were derived by converting needle dry weight to one-sided needle areas through the relationship between SLA and the position of the needles in the canopy (distance to top, and height relative to the maximum tree height in the plot). Further details can be found in Magnussen and Boudewyn (1998).

CASI images of the trial area were acquired on September 27, 1996 at 19:50 G.M.T. The weather conditions were clear and the sun-angle was 39.4°. A composite and rectified image mosaic using channel(s) 1-8 (437.5-847.2 nm) was assembled for the area (Figure 1) with a pixel size of 60 cm. Full coverage was obtained for 27 plots, but only 21 plots had the full compliment of field data used in this study.

NDVI values were computed for each pixel as $NDVI = \frac{(\alpha_{nir} - \alpha_{vis})}{(\alpha_{nir} + \alpha_{vis})}$ where α_{nir} and α_{vis} represent surface

reflectances averaged over ranges of wavelength in the visible (channel 5, $\lambda \sim 656.0$ nm, "red") and near infrared (channel 8, $\lambda \sim 847.2$ nm) regions of the CASI spectrum, respectively (Tucker 1979).

To explore the association between spatial autocorrelation of NDVI and plot mean values of basal area and volume we computed directional spatial autocorrelation coefficients (Cliff and Ord 1981) of NDVI-values in a plot. Coefficients were computed for first-order neighboring pixels (pixels sharing one common border), second-order neighbors (pixels separated by a first-order neighbor), and third-order neighboring pixels (pixels separated by a first- and a second-order neighbor pixel). Average values were computed as weighted means over the four cardinal directions (weight: sample size). According to (Carlson and Ripley 1997) one should expect the relationship between NDVI to be impacted by the homogeneity of the canopy structure. Spatial autocorrelations provides an measure of patchiness of the NDVI 'image'.

An explorative Wavelet analysis with the same purpose as the spatial autocorrelation was carried out on the NDVI 'images' of each plot (Jawerth and Sweldens 1993). We used the father (Φ) and female (Ψ) Haar wavelets (Daubechies 1992) with scale factor J ($J = 1, 2$, and 3) in the analyses. The mean absolute deviation (MAD) of the wavelet coefficients $\Phi^k(2^{-J} \cdot x - m, 2^{-J} \cdot y - n)$ and $\Psi^k(2^{-J} \cdot x - m, 2^{-J} \cdot y - n)$ were computed for the two-directional smooth ($d_{0,0}^0$), the vertical detail ($d_{0,0}^v$), the horizontal detail ($d_{0,0}^h$), and the diagonal detail ($d_{0,0}^d$). X and y are the row and column number of the pixels in the plot, respectively; m is the translation in the x - or y -direction. Throughout, $m=0$, and $n=0$. Superscript k is a direction indicator: $k=h$ (horizontal), v (vertical), $h \otimes v$ (horizontal $\times$ vertical), and d (diagonal). The mean absolute deviation of these coefficients is a measure of image 'energy' in the various direction and resolutions.

Ordinary least squares regression models (Draper and Smith, 1981) to predict volume, basal area and leaf area index from NDVI statistics (means, variances, autocorrelation) and wavelet MAD-values were explored.

RESULTS AND DISCUSSION

Total stem volume per hectare in the 21 included plots varied from a low of 246 m^3 to a high of 573 m^3 with a median value of 449 m^3 . Basal area varied accordingly from 32 $m^2 \cdot ha^{-1}$ to 64 $m^2 \cdot ha^{-1}$ (median: 54 $m^2 \cdot ha^{-1}$). LAI values went from 2.0 to 4.6 (median: 3.5). Plot values of volume, basal area, and LAI represents a wide range of canopy structures, from very dense (~ 4000 stems $\cdot ha^{-1}$) with small crowns (length ~ 6 m) to fairly open (~ 800 stems $\cdot ha^{-1}$) with long lush crowns (length ~ 13 m). LAI values reported here compared favorably with LAI-values published elsewhere for mono-specific coniferous stands in the northern hemisphere (Binkley and Reid 1984, Gholz, Curran, Kupiec and Smith 1997, Magnussen et al. 1986, Moir and Francis 1972) falls in the range of the Shawnigan plot values. A sample of the most promising exploratory correlations between volume, basal area, and LAI on one hand and a suite of statistics derived from the CASI images are presented in Table 1. Clearly, NDVI provides the strongest positive association with volume, basal area, and LAI. Low variability in the reflectance value of a channel was indicative of plots with above average values of volume, basal area and LAI. Variance of reflectance value register the spatial heterogeneity in the underlying feature space. Given the importance of spatial variation for the primary production processes (Ghent and Franson 1986, Hastings 1990, Legendre 1993, Liu and Burkhart 1994, Pacala and Deutschman 1995, Wulder, Franklin and Lavigne 1996) it is important to include aspects of feature variance in prediction of production of biomass and wood volume. Our wavelet analysis, although less convincing, produced similar results as the spatial autocorrelation, but did, otherwise not appear to offer the promised advantages of multi-scale resolution analysis as anticipated (Kolaczky 1996, Raffy 1994b). Simple explorations of spatial covariances (Saint-Onge and Cavayas 1995, St-Onge and Cavayas 1997) has more appeal due to our ability to interpret the estimated image features.

Figure 3 shows in three scatter plots the relationship between $NDVI_{plot}$ and VOL, BA, and LAI. A fourth scatter plot illustrates the tight relationship between average plot LAI values and the total stem volume they contain. The biomass survey of the Shawnigan trial (Brix 1993) and subsequent analyses (Magnussen and Boudewyn, unpublished) supported the contention of a linear relationship between needle dry weight and stem volume. NDVI appears to be a consistent predictor of both VOL, BA and LAI throughout the observed range. Note, however, the very limited range of observed values, the difference between the highest and the lowest was a mere 0.03, or barely 4%. This short range makes predictions extremely sensitive to atmospheric attenuations of the NDVI values (Carlson and Ripley 1997). The frequently observed saturation of NDVI at LAI values

above 3 did not materialize (Carlson and Ripley 1997, Leprieur et al. 1996, Liu and Huete 1995). A main contributor to the among-plot differences in NDVI-values is the effective crown area, F (Jupp and Walker 1997). F is the areas of crowns after discounting gaps and openness. NDVI was negatively correlated with F (-0.32). Figure 4 shows the within plot variation of NDVI values for the two plots with the highest and the two plots with the lowest mean.

Prediction of stem volume, basal area, and LAI from NDVI, spatial autocorrelation, and variance of reflectance value was attempted by exploring a multitude of linear regressions. The most promising combination of predictors in terms of residual standard deviation, low colinearity (Fox and Monette 1992) and Bayes information criteria, (BIC, Ledwina 1994). Equation (1) gives the chosen regression model (all predictors are sample estimates on a per plot basis)

$$\text{Eq. (1)} \quad VOL_{plot} = \overline{VOL}_{plot} + 1230.6 \cdot NDVI_{plot} - 2.054 \sqrt{\sigma_{channel3reflectance}^2} - 2932 \cdot \rho_1 \cdot \rho_3$$

where ρ_i is the average i th-order correlation coefficient of within plot pixel values of NDVI. The expected prediction error of equation (1) is 10% ($r^2=0.61$, $F_{\text{regression}} = 9.22$, $P < 0.001$). Figure 5 depicts the field estimates of stem volume plotted against the predicted values (the solid line is the line of perfect predictions). No consistent pattern emerged when the five plots with residuals $> 9\%$ of the predicted value were scrutinized. They represent both lightly and heavily thinned plots, they include three different fertilizer regimes and the average crown size, density, and number of overtopped trees did not deviate in any systematic way from the remaining plots. Note the order of magnitude differences in the regression coefficients which is a cause of concern (Myers 1986) in terms of the robustness of the predictions. As formulated, the predictions will be very sensitive to errors in the predictors (Fuller 1987).

CONCLUSIONS

The results of this study were in many aspects "typical"; they illustrate that high resolution scenes contains enough information to discriminate effectively between areas with high and low values of LAI, volume and other canopy proxies of biomass (Gholz, Curran, Kupiec and Smith 1997, Gougeon 1995, Naesset 1997, Saint-Onge and Cavayas 1995). Yet the real challenge for wider applications in forest inventories lies in making these model-based predictions applicable outside the scene from which they were derived, our results are strongly scale dependent (Raffy 1994a) and we expect that minor changes in atmospheric conditions will modify the derived relationship.

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NDVI plot image attribute	VOL ($\text{m}^3 \cdot \text{ha}^{-1}$)	BA ($\text{m}^2 \cdot \text{ha}^{-1}$)	LAI
mean NDVI of plot	0.79**	0.56**	0.83 **
variance of channel 3 ($\lambda \sim 500 \mu\text{m}$)	-0.58**	-0.52**	-0.59 **
variance of channel 6 ($\lambda \sim 700 \mu\text{m}$)	-0.71**	-0.47**	-0.75**
third-order spatial autocorrelation of NDVI	-0.41 n.s.	-0.43*	-0.33 n.s.
fourth-order spatial autocorrelation of NDVI	-0.34 n.s.	-0.27 n.s.	-0.29 n.s.
MAD of wavelet coefficients, horizontal detail	-0.45*	-0.45*	-0.42 n.s.
MAD of wavelet coefficients, vertical detail	-0.21 n.s.	-0.52**	-0.10 n.s.

Table 1. Product moment correlations between volume (VOL), basal area (BA), and leaf area index (LAI) and various image attributes.

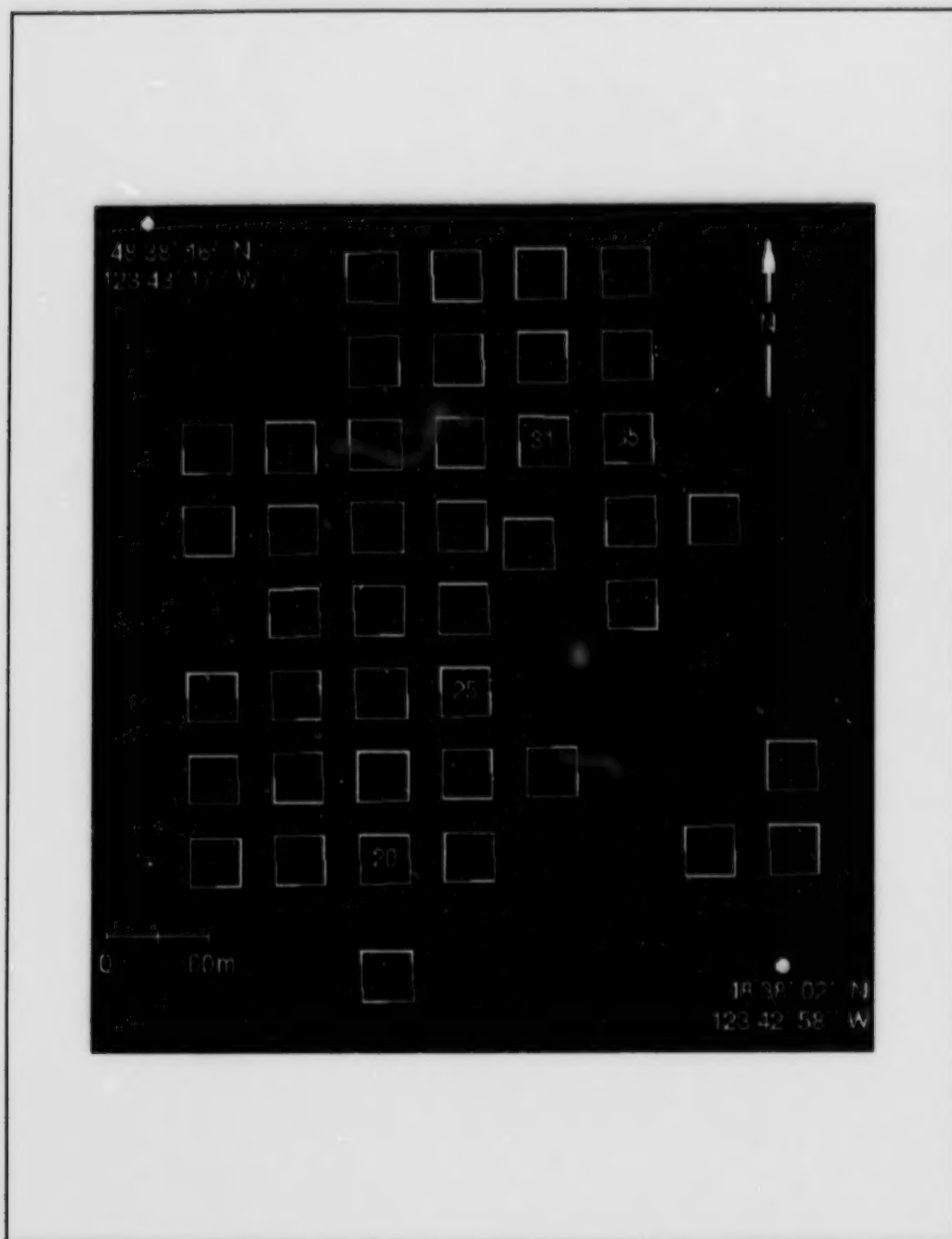


Figure 1. Overview of the Shawnigan trial area north of Victoria, Vancouver Island, British Columbia. Plots shown in close-up view in Figure 2 are numbered.

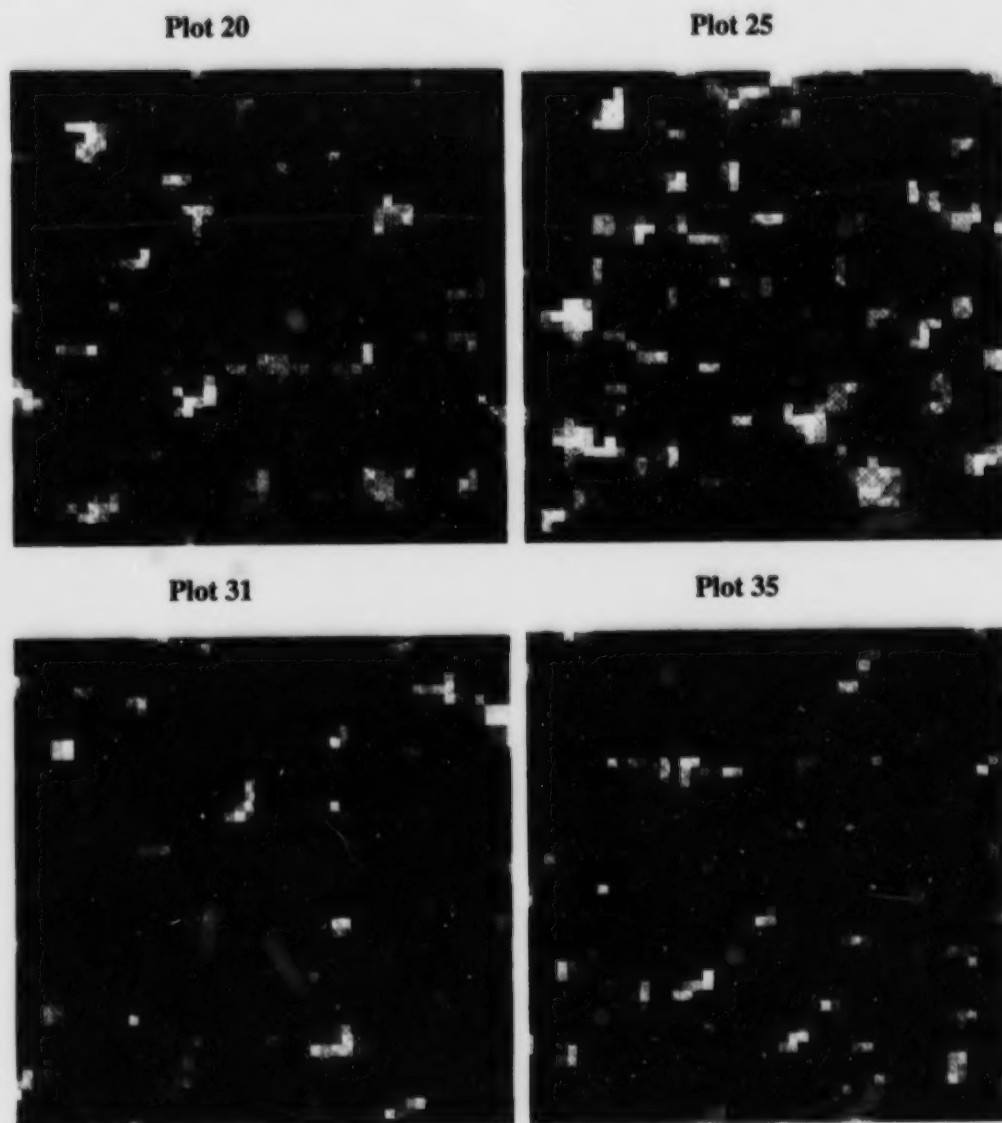


Figure 2. CASI close-up images of four plots, two with top ranking NDVI values (20 and 35) and two with lowest ranking NDVI values (25 and 31).

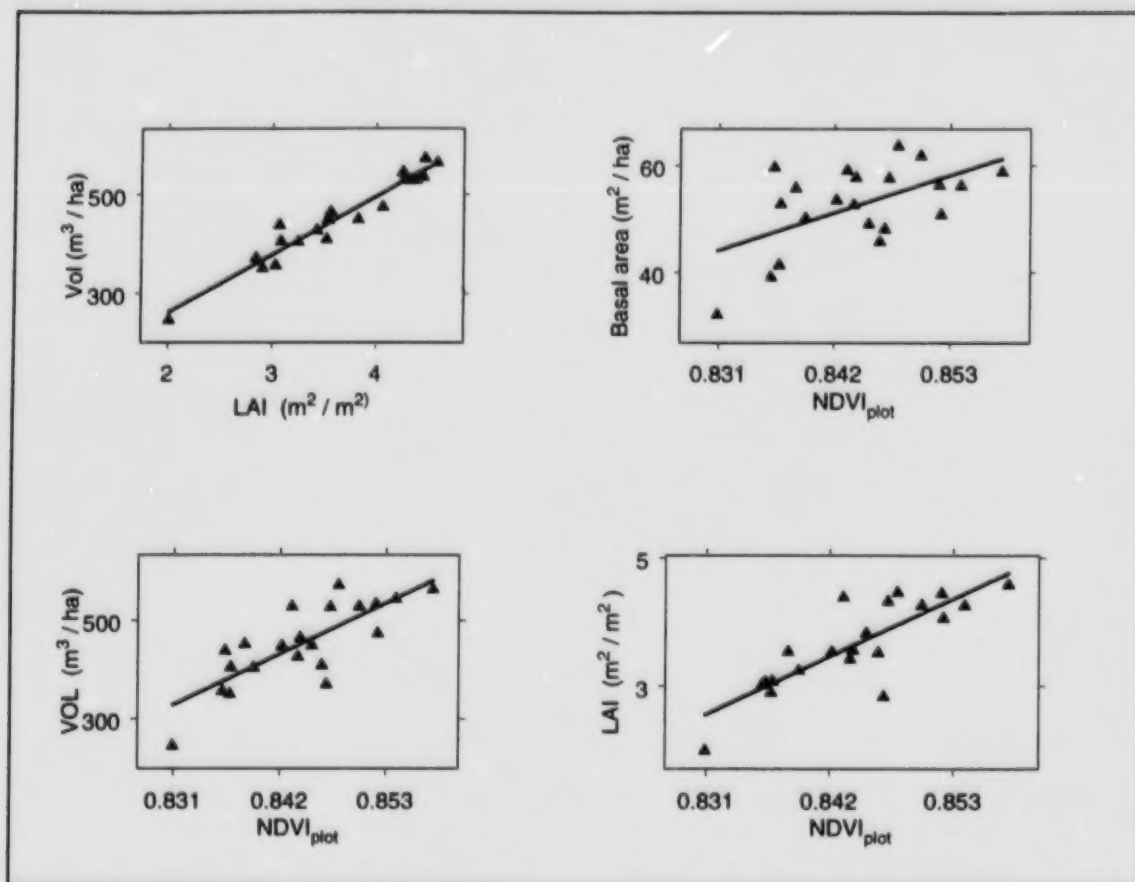


Figure 3. Scatter plots of plot mean values of volume, basal area, leaf area index, and NDVI..

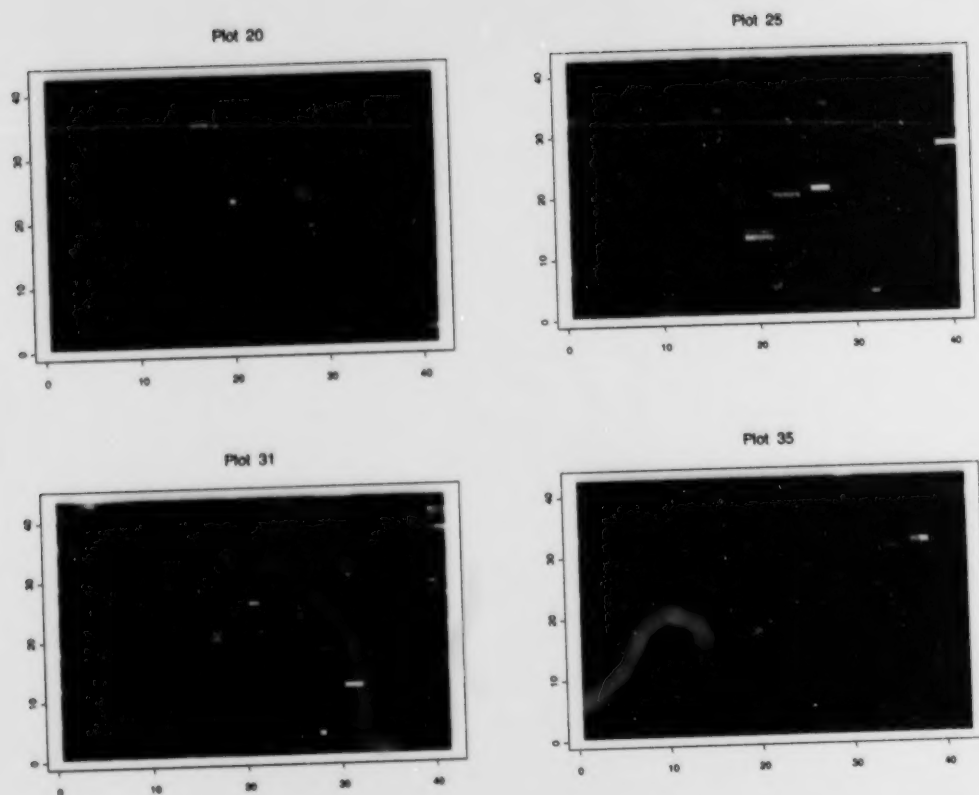


Figure 4. Four plots with contrasting NDVI values (clockwise starting in upper left corner: high, low, low, high).

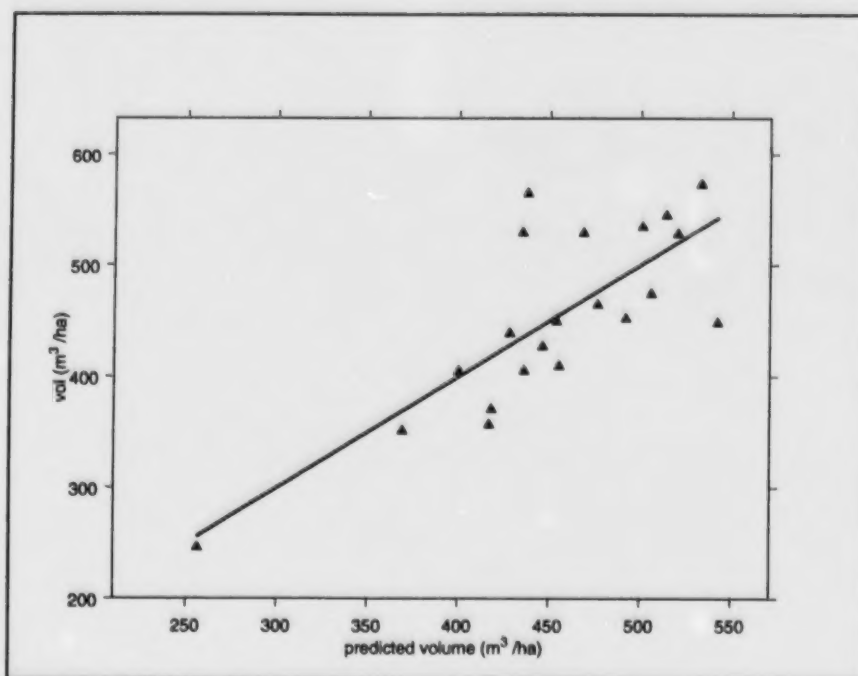


Figure 5. Estimated plot mean values of stem volume against predicted stem volume (from equation 1).

ESTIMATION OF CROWN CLOSURE AND SPECIES COMPOSITION FROM HIGH RESOLUTION MULTISPECTRAL IMAGERY

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ABSTRACT

In this study, airborne multispectral video camera images were acquired with 32 cm by 25 cm pixel resolution from approximately 150 m above a mature forest ecosystem near Barrier Lake in Kananaskis Country, southwestern Alberta. Alberta Vegetation Inventory (AVI) data, including species composition and crown closure, were collected at 22 plots scattered throughout several pure and deciduous and coniferous dominant mixed-wood stands. *Feature-based* methods of image analysis used a series of filtering, classification and spatial operations to separate individual features such as tree crowns, understory, and shadows resolved in the image data. There were no statistical differences between crown areas measured at the plot level when compared to similar measurements derived from the digital image. Species composition accuracy was higher for trembling aspen than for lodgepole pine and white spruce. A contextual classifier was used to construct a forest composition label similar to that employed by the AVI for species composition and crown closure. Additional work in developing estimates of stand volume using models based on image and AVI data (crown closure, stems/ha, species composition, stand height) is planned for softwood, hardwood and mixed-wood species.

Keywords: airborne multispectral video, feature-based image processing, vegetation, forestry, forest inventory.

RÉSUMÉ

ÉVALUATION DE LA FERMETURE DU COUVERT ET DE LA COMPOSITION DES ESPÈCES À PARTIR D'IMAGES MULTISPECTRALES À HAUTE RÉOLUTION

Dans le cadre de cette étude, des images multispectrales ont été prises par caméra vidéo aéroportée avec une résolution de pixel de 32 cm x 25 cm à environ 150 mètres au-dessus d'un écosystème forestier adulte situé à proximité du lac Barrier dans la région de Kananaskis dans le sud-ouest albertain. Des données de l'Alberta Vegetation Inventory (AVI), y compris des données sur la composition des espèces et la fermeture du couvert, ont été recueillies dans 22 parcelles réparties sur plusieurs peuplements purs et décidus et peuplements mixtes à dominance résineuse. On a eu recours à des méthodes d'analyse d'images basées sur les entités mettant en œuvre diverses techniques de filtrage, de classification et de manipulation spatiale aux fins de la séparation des caractéristiques individuelles, notamment des houppiers, des sous-étages et des ombres extraites des données d'image. Aucune différence statistique n'a pu être constatée entre les mesures de projection des houppiers relevées à même les parcelles et les mesures semblables dérivées de l'imagerie numérique. On a déterminé avec plus d'exactitude la composition des espèces des peuplements de peupliers faux-trembles que celle des peuplements de pins tordus latifoliés et d'épinettes blanches. On s'est servi d'un classificateur contextuel pour

réaliser une étiquette de la composition forestière semblable à celle utilisée pour l'AVI aux fins de la détermination de la composition des espèces et de l'évaluation de la fermeture du couvert. On prévoit également entreprendre des travaux supplémentaires pour l'évaluation du volume ligneux des peuplements résineux, décidus et mixtes à partir de modèles créés à l'aide de données d'image et de données de l'AVI (fermeture du couvert, tiges/ha, composition des espèces, hauteur des peuplements).

INTRODUCTION

The Alberta Vegetation Inventory (AVI) is an integrated inventory classification system that is based upon air photo interpretation of medium-scale aerial photographs to define forest stands based on species composition, height, crown closure, age, and productivity (Alberta Forestry, Lands and Wildlife 1991). The AVI provides very detailed spatial data that is utilized by Alberta forest managers who are required to manage the renewable resources on Crown forest lands in an ecologically sustainable manner (Alberta Forest Conservation Strategy 1997). They must also provide increasingly detailed estimates of the costs and effects of alternative management practices on tree and stand growth and yield, biodiversity, and conservation of wildlife habitat. AVI data alone are insufficient to meet these needs. The information required could be obtained by installing large numbers of ground-measured plots, but such plots are costly to establish, measure and maintain. The challenges to meet these information needs creates opportunities to investigate the potential role of and use in high resolution airborne or satellite remote sensing data that would complement AVI data acquisition.

Recent research has suggested traditional per-pixel image processing techniques will not be effective nor satisfactory for classification of high resolution data (Guindon 1997). A shift in analysis methods from *per-pixel* analysis (Treitz et al. 1985; Hughes et al. 1986; Franklin 1994) to *window-based operators* (Yuan et al. 1991) and *feature extraction* (Gougeon 1995a, b; St-Onge and Cavayas 1995; Hay et al. 1996; Gougeon 1997a, b) is evident in high spatial resolution image analysis. The image processing field is moving from a focus on *pixels* (picture elements) and *texels* (texture elements) to *mixels* (mixture elements) and *felxels* (feature elements). In this study, high resolution video images were acquired by the Multispectral Video (MSV) package (Roberts, 1995) in Kananaskis Country, with the objective of determining the extent that forest crown closure and species composition could be derived from existing *feature-based* image analysis methods.

STUDY AREA AND DATA COLLECTION

STUDY SITE AND FIELD DATA COLLECTION

The study site was located on a south-west facing slope near Barrier Lake, in Kananaskis Country, Alberta (51.02 N, 115.01 W) at an elevation of approximately 1400 m. This site is within the Montane Forest Region M.5 (Rowe 1972) that is dominated by trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), lodgepole pine (*Pinus contorta* Lamb.), and white spruce (*Picea glauca* [Moench] Voss). Archibald et al. (1996) provide detailed descriptions of the plant community types in the study area. AVI stand descriptors were determined on July 10, 1996, at 22 field plots located on 8 transects surveyed on an east/west gradient to sample the elevational and slope distribution in the area. Each plot measured approximately 10 m by 10 m. For every stem with a diameter at breast height (DBH) greater than 10 cm, tree height, DBH, and age were recorded, and understory species were noted in ocular quadrants with percent cover estimates. Percent species composition was determined for each species based on tree frequencies, and crown closure was measured with the aid of a spherical densiometer. Each plot was subsequently labeled with the appropriate AVI code. Plot centres were located with differentially-corrected, Trimble Navstar Global Positioning Satellite (GPS) observations.

MULTISPECTRAL VIDEO CAMERA IMAGERY

On July 11, 1996, under predominantly clear skies, three co-registered and calibrated Sony XC-75 CCD NTSC video cameras were flown from approximately 150 m above ground to yield a pixel size of 0.32 m by 0.25 m (Roberts, 1995). The video cameras were equipped with spectral filters whose effective bandwidths

ranged from 490 to 565 nm, 585 to 660 nm, and 720 to 850 nm, respectively. Four overlapping lines at this altitude were flown, yielding thirty-four, 512 pixel by 486 line images that were frame-grabbed approximately every second, and downloaded immediately following the flight. Cardboard calibration panels of the three primary colours (plus a white reference) measuring 1 m² were placed at the beginning of the flight line and were constantly monitored for reflectance during the mission using the ASD Personal Spectroradiometer II. Reflectance calibration was not possible because the calibrated reflectance measurements showed significant saturation, and the calibration panels on the images appeared to contain significant 'blooming' (Roberts 1995). A companion study of the variability in pseudo-invariant object reflectance measured in the adjacent parking lot is described by Milton et al. (1997).

Markers placed at the beginning and end of each field transect were clearly visible on the images and were used to position the field plots on each frame. The field plots were later located more precisely with the aid of the on-board Loran-C GPS receiver which tagged each frame centre. The data acquisition mission was accomplished in less than 10 minutes of flying time, and no significant changes in extant environmental conditions were noted. To allow for multi-image comparisons, the auto-gain function of the digital video cameras was disabled.

METHODS

AERIAL IMAGE PRE-PROCESSING

Band-to-band registration was performed on each of the images from the three digital cameras to correct the camera mis-alignment that had occurred during image acquisition. The images were corrected for atmospheric aerosols using the dark object subtraction method (Chavez 1988) where histograms of each image were analyzed to find the lowest digital numbers. Radiometric matching of adjacent frames or frames located at different ends of flight lines was not necessary because of the short time period that elapsed between frames and the relatively constant environmental conditions that were noted during the data acquisition. In absolute radiometric terms, the images were not calibrated and only the raw digital numbers (DN's) were adjusted for dark-object reflectance (McCreight et al. 1994; Pellikka 1996).

FEATURE EXTRACTION FOR CROWN CLOSURE CALCULATION

Two tree crown delineation techniques were compared to determine which method was preferable for identifying individual tree crowns. The first technique employed an image classification approach to isolate tree crowns (Biging et al. 1995) by deriving 'pure' species signatures to classify individual tree species on the video images (Gerylo et al. 1997; Fish et al. 1995). Signatures of individual tree species were derived manually from the sunlit side of tree crowns (Hughes et al. 1986) using the ground survey information, and used in a per-pixel maximum likelihood classifier algorithm. The resulting classified image represented the dominant tree species. This technique is considered an effective technique for classifying tree species on MEIS high resolution images (Gougeon and Moore 1989; Gougeon 1995a; Gougeon 1997b). The classified image was subsequently recoded into one class to represent the areal extent of tree crowns.

The second tree crown delineation technique used a Laplacian 'second derivative' filter for isolating tree crowns. The Laplacian filter can be used to emphasize maximum values found throughout the images without any concern to edge direction because the filter highlights edges having both positive and negative brightness slopes. The second derivative is the rate of change in the measured value and has wide applicability in remote sensing feature extraction. Numerous uses of Laplacian operations are documented in other image processing applications. For example, Chavez and Gardner (1994) showed the importance of the second derivative in extracting spatial amplitude and variability information from sonar imagery. In this study, a second derivative filter was hypothesized to be an effective separator of the bright tree crowns from the darker (shaded) canopy understory and shaded side of the crown. A 9 pixel by 9 pixel Laplacian filter was passed across the image. This window size was determined after a series of iterations were run with various window sizes, whereby this window appeared to best emphasize maximum image values, and to separate tree crowns in known areas. All positive slope values thought to represent tree crown pixels, were then thresholded and written to a new image

channel. These positive values were assigned a value of 1 (representing tree crowns), while the negative values received a value of 0 (representing non-tree crown space).

With both techniques crown closure was determined by calculating the percentage of pixels representing tree crowns that were found within a fixed area window. A 33 pixel by 33 pixel window was used for these calculations. Results of iterative tests suggested that this was a stable area over which the calculations could be made, and this window size was close to the 100 m² plots used in the field.

Crown closure (CC) accuracy was derived from each of the two feature extraction techniques by calculating the crown closure error for each plot relative to the field measurement. Crown closure in the field was measured at 5 point locations and averaged for each plot. The point locations included plot centre and one reading located 2 - 3 metres away from each plot corner along a diagonal towards plot centre to avoid the influence of vegetation from outside the plot. The CC error in percentage was calculated for each plot by subtracting the image based estimate of crown closure from its field observation, and dividing this value by the field observation, and multiplying by 100.

A one-way analysis of covariance design was implemented to determine if statistical differences in crown closure existed between crown closure measured in the field relative to the same trees estimated by image classification and Laplacian filter techniques. An important consideration is that crown areas of individual trees that make up the crown closure for a stand are species dependent. Differences in tree structure and crown area are particularly noticeable between hardwood and softwood species. A covariate term was therefore necessary to account for the influence of species on crown areas by grouping species composition into hardwood, softwood, and mixed wood. A hardwood or softwood stand was defined by the dominant species that comprised at least 80 percent of the stand, otherwise it was considered a mixed-wood stand. The response variable was percent crown closure measured within each of the plots. If there were significant differences among crown closure estimates, then the Bonferroni multiple mean comparison test (Neter et al. 1990) was employed.

FEATURE EXTRACTION FOR ESTIMATION OF SPECIES COMPOSITION

Stand species composition was estimated by combining the results of high pass filtering, image classification, and spatial operations. Individual trees often appear on high resolution digital images as bright regions, and the centre of a tree crown generally has a single bright pixel, relative to neighboring pixels that decrease slightly in intensity. Other work has shown (e.g., Eldridge and Edwards 1993; Fournier et al. 1995; Gougeon 1995b) that this bright pixel represents the highest part of the tree crown (crown apex) because it is not largely affected by shadows. Rather than identifying each tree stem location manually, a simple automated method based on a maxima filter (Gougeon and Moore 1989; Hay et al. 1996; Gougeon 1997b) was used to flag tree stem locations. While this filter is known to be effective for isolating a large portion of individual tree stems, for the purposes of this study, a rule-based maxima filter was designed to identify pixel locations where individual tree stems appeared on the DFC images with multiple maxima.

A 3 pixel by 3 pixel filter was built to 'flag' individual pixel locations. If the centre pixel value within the filter was larger than all of its 8 neighbors, it received a value of 1. If the centre pixel value was smaller than one or more of its immediate neighbors it received a value of 0. If one of the surrounding neighbours had the same DN value as the centre pixel, and all other neighbours had a lower value, then a second channel of image data was used to determine which pixel should receive the tree stem flag. This filter was applied to the NIR channel, because it was hypothesized to have the greatest contrast, and vegetation reflects most strongly in this portion of the electromagnetic spectrum. A Normalized Difference Vegetation Index (NDVI) image was then used to break the ties that occurred when multiple maximum values were found. The maxima filter was run across the entire image, flagging each individual tree, and writing the results to a new image channel. Local understory maxima may also be identified as tree stems in less dense regions. To eliminate this understory influence, a logical AND operation was performed with the tree crown image (from Laplacian filter) and the maxima filter tree stems image. This yielded a final image that depicted the spatial locations of individual tree stems (Figure 1).

To determine species composition, a species identifier was required for each of the tree stems. The image classification from the sunlit side of tree crowns was used to assign the species identifier for each stem. The tree stem image was multiplied by the species classification to assign each stem an appropriate species label. Species composition in percentage units was estimated by calculating the percentage of each tree species found within the fixed window. The 33-pixel by 33-pixel window was used to emulate the actual plot dimensions found in the field. The number of stems for each species was divided by the total number of tree stems in the window from which species composition was determined.

Species composition accuracy was measured by calculating the mean error of estimating species and the average percent accuracy for each species (lodgepole pine, white spruce, and trembling aspen). This method of accuracy assessment, described by Fent et al. (1995), has been shown to be an effective statistic for measuring the accuracy between actual and interpreted values. This test compared interpreted (image processing estimates) values to their actual field values (field estimates), resulting in a mean error of estimation (E) for each variable tested. Average (percent) accuracy from the image processing technique was then calculated as $(100 - E)$. Correlation statistics were also examined to determine the strength of correlation between field and image processing estimates of species composition.

RESULTS AND DISCUSSION

CROWN CLOSURE ESTIMATION

Tree crown images were created from the image classification (Figures 1b, c) and Laplacian filter (Figure 1e) methods, from which a table that compared crown areas was created (Table 1). The image classification approach based on training signatures generated from the sun-lit side of tree crowns resulted in an average accuracy rate of 78% (Table 2). These results are consistent with other classification results of individual tree species based on high resolution images (Gougeon, 1995a; Meyer et al. 1996). Trembling aspen was classified most accurately with 97% of training pixels correctly classified. The lodgepole pine and white spruce classes had lower accuracy rates of 74% and 63%, respectively. The accuracy of conifers were lower because of the confusion between the lodgepole pine and white spruce class signatures. This confusion is a result of their similarities in crown structure and appearance. The three-band images did not provide sufficient multispectral data to distinguish between these two conifer species consistently. For improved classification of conifers, image dates at different phenological stages, and additional spectral bands of narrower band width, or, the addition of DEM data and image texture algorithms should be used to increase the separability between these two species.

Use of the tree species classification method for definition of tree crowns (Figure 1c) resulted in an average accuracy of 47.7% (Table 1). Crown closures were generally overestimated because of classification errors where understory species were misclassified as overstory tree species. These results are consistent, however, with a similar test conducted by Biging et al. (1995). The tree crown image generated by the Laplacian filter (Figure 1d) and thresholding the resulting image (Figure 1e) resulted in crown closure estimates that were more similar to their field estimates with an average accuracy of 86% (Table 1). The Laplacian filter constructed a crown-specific mask, whereby all understory vegetation were eliminated by virtue of the differences between bright and dark (shaded) portions of the canopy. An accurate representation of the spatial organization of tree crowns could be generated once all positive filtered values are thresholded into one class.

There was a significant difference in the crown closure methods based on the analysis of covariance design (Prob. > $F = 0.0001$). The species covariate term was also significant (Prob. > $F = 0.0005$), which suggested the analysis of covariance design was appropriate for this study. The Bonferroni multiple mean comparison test was necessary to determine which of the two methods for estimating crown closure were significantly different from the field measurements. At the 5% probability level, there was no difference between the field measured and Laplacian filter estimated crown areas. There was a significant difference between the crown areas derived from the image classification and crown areas from both the field measurements and Laplacian filter method. The Laplacian edge detector filter can be used as a simple and effective tool for delineation and separation of tree crowns from the canopy understory as expressed on the video camera images.

ESTIMATION OF SPECIES COMPOSITION

The first processing step in the calculation of species composition was to identify individual tree stems (Figure 1f). A qualitative visual analysis of results from the rule-based maxima filter suggested that the majority of tree stems appeared to be identified on the digital frame camera images. The use of the tree crown mask was effective in eliminating flagged values found within the understory, thereby exclusively isolating tree stems. The tie-breaking rule which was used to identify tree stem locations when two or more maximum values were present in the window was moderately effective in identifying the primary tree stem location. Ties were not broken in many cases because identical values were also found in the second image channel. The rule-based maxima filter was effective for identifying individual aspen trees, but identifying conifer stems proved more difficult. Increasing distances from nadir resulted in multiple conifer stems being identified due to radial displacement effects that increased the area of visible conifer needles. This served to flag more than one maximum value location under the small window. The isolation method is only considered an effective technique for identifying individual tree stems found at or near the nadir point of the image.

Species composition percentages were estimated with an average accuracy of 83% based on lodgepole pine, white spruce and trembling aspen (Table 3). The percentage of trembling aspen was estimated most accurately, while lodgepole pine and white spruce were estimated least accurately. Some plots exhibited lower accuracy rates because classification errors occurred between the two conifer classes. In some images lodgepole pine was classified as white spruce and vice-versa, while in other images, conifer stems were over-estimated (Table 3). The poor separability between conifer species was likely attributed to their similarity in spectral reflectance patterns at the time of year the data was flown. Subtle species spectral differences may not be detectable in July when conifer species are often at their maximum photosynthetic capacity. Additional data flown earlier in the year to represent a different phenological growth stage may be needed to separate these two species.

Some simple additional methods may improve these results. A modification of the rule-based maxima filter plus new rules such as how to handle three or more identical maximum values should aid in increasing species composition estimates by more accurately flagging all visible tree stem locations. Locating plots exclusively near image centres to reduce radial image displacement effects due to tree heights should also help to reduce the over-identification of conifer tree stems. Additional image bands and image acquisition dates should be explored to determine if stronger classification and species composition results could be achieved.

CONCLUSIONS

The results of feature extraction techniques (Laplacian filter, image classification, and a rule-based maxima filter) and logical image thresholding were evaluated to determine their effectiveness in performing an AVI classification on the available multispectral images. A supervised classification based on sunlit pixels and a Laplacian second derivative filter was compared for extracting tree crowns from the overstory canopy. A spatial operator was applied to the results of these operations to estimate percent stand crown closure. Tree crowns extracted by the Laplacian filter were statistically similar to field measurements based on a spherical densiometer. A rule-based maxima filter was employed for estimation of stand species composition. Trembling aspen was classified with higher accuracy (88.5%) when compared to lodgepole pine (75.6%) and white spruce (83.7%) (Table 3). Additional data at a different date such as early in the growing season to represent a different phenological stage is recommended to improve conifer species discrimination. Future work will employ estimates of crown closure and stems/ha density in models to estimate stand volume for hardwood, softwood and mixed-wood species.

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Plot #	Field Estimate	Image Classification	Laplacian Filter	% Error from Image Classification	% Error from Laplacian Filter	Accuracy (%) from Image Classification	Accuracy (%) from Laplacian Filter
1	61	80	50	-31.1	18.0	68.9	82.0
2	42	68	46	-61.9	-9.5	38.1	90.5
3	57	73	44	-28.1	22.8	71.9	77.2
4	41	78	51	-90.2	-24.4	9.8	75.6
5	32	49	40	-53.1	-25.0	46.9	75.0
6	38	83	51	-118.4	-34.2	-18.4	65.8
7	37	64	44	-73.0	-18.9	27.0	81.1
8	52	69	46	-32.7	11.5	67.3	88.5
9	39	50	40	-28.2	-2.6	71.8	97.4
10	40	86	50	-115.0	-25.0	-15.0	75.0
11	50	88	50	-76.0	0.0	24.0	100.0
12	49	61	43	-24.5	12.2	75.5	87.8
13	39	38	39	2.6	0.0	97.4	100.0
14	46	74	46	-60.9	0.0	39.1	100.0
15	43	56	42	-30.2	2.3	69.8	97.7
16	32	61	45	-90.6	-40.6	9.4	59.4
17	52	45	38	13.5	26.9	86.5	73.1
18	41	54	43	-31.7	-4.9	68.3	95.1
19	39	34	39	12.8	0.0	87.2	100.0
20	51	79	50	-54.9	2.0	45.1	98.0
21	41	61	44	-48.8	-7.3	51.2	92.7
22	36	62	45	-72.2	-25.0	27.8	75.0
Average Accuracy						47.7	85.8

Table 1. Estimation of crown closure.

	Null	Pine	Spruce	Aspen
Pine	2.9	73.5	23.4	0.2
Spruce	1.8	35.1	62.8	0.3
Aspen	2.5	0.2	0	97.3
Average Classification Accuracy = 77.9%				

Table 2. Confusion matrix from the tree crown image classification.

Plot- Id	Field Estimates				Image Processing Estimates				Accuracy of Estimates (%)						
	Pine	Spruce	Aspen		Deciduous	Pine	Spruce	Aspen		Deciduous	Pine	Spruce	Aspen		Deciduous
			Conifers	Conifers				Conifers	Conifers				Conifers	Conifers	
1	50	0	50	50	50	48	8	44	56	44	98	92	94	94	94
2	68	16	16	84	16	29	58	13	87	13	61	58	97	97	97
3	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
4	0	0	100	0	100	0	4	96	4	96	100	96	96	96	96
5	83	0	17	83	17	19	6	75	25	75	36	94	42	42	42
6	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
7	0	17	83	17	83	16	5	79	21	79	84	88	96	96	96
8	100	0	0	100	0	14	86	0	100	0	14	14	100	100	100
9	88	0	12	88	12	89	0	11	89	11	99	100	99	99	99
10	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
11	8	8	84	16	84	3	0	97	3	97	95	92	87	87	87
12	8	25	67	33	67	90	10	0	100	0	18	85	33	33	33
13	75	25	0	100	0	92	0	8	92	8	83	75	92	92	92
14	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
15	75	0	25	75	25	33	47	20	80	20	58	53	95	95	95
16	50	6	44	56	44	22	6	72	28	72	72	100	72	72	72
17	25	25	50	50	50	76	24	0	100	0	49	99	50	50	50
18	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
19	88	12	0	100	0	85	8	7	93	7	97	96	93	93	93
20	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
21	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
22	0	0	100	0	100	0	0	100	0	100	0	0	100	100	100
Average accuracy (%)											75.6	83.7	88.5	88.5	88.5
Overall accuracy (%)											82.6				

Table 3. Comparison of field and image processing estimates of species composition.

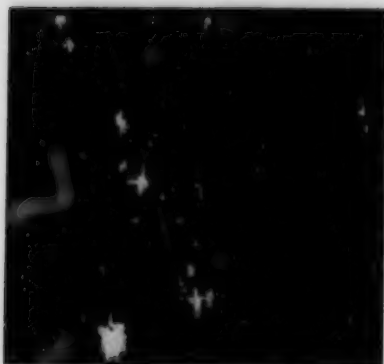


Figure 1a.
Sub-region of study area.

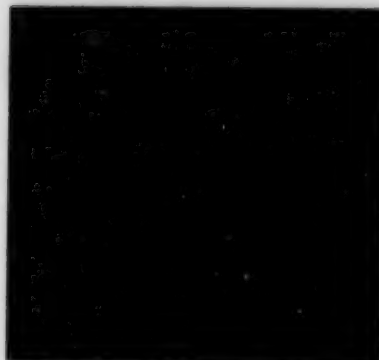


Figure 1b.
Image classification of tree species
type; Red (Pine), Green (Spruce),
and Blue (Aspen).



Figure 1c.
Tree crown image from the species
classification image.

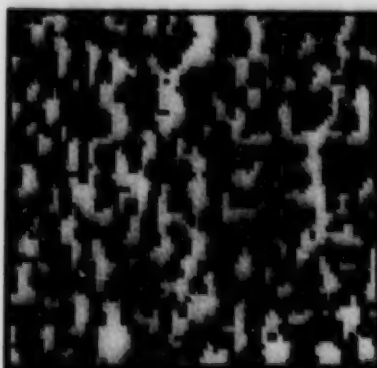


Figure 1d.
Results of the 9 by 9 Laplacian filter
run over the NIR band.

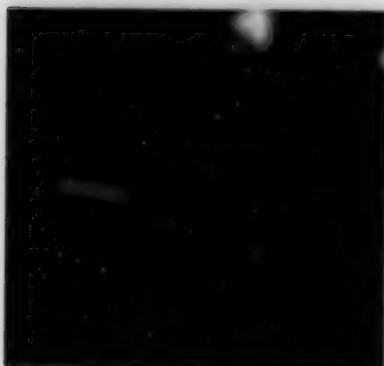


Figure 1e.
Tree crown image resulting from
thresholding of the Laplacian-filtered
image.

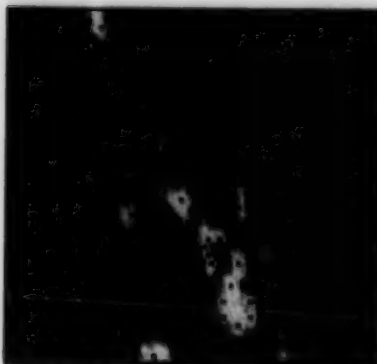


Figure 1f.
Individual tree stems, from the rule-
based maxima filter, superimposed
on the NIR image.

FOREST STAND STRUCTURE MAPPING USING A SPECIES-CONTROLLED TEXTURAL APPROACH

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ABSTRACT

The visual texture of aerial photographs helps interpreters in their assessment of the structural characteristics of forest stands. Textural features can also be evaluated by the directional semivariogram measured on panchromatic one meter digital images and can be linked statistically to stand structure parameters. However, the mathematical relationships between image texture and stand structure is influenced by the dominant species of the stand. We have assessed these various relationships through multiple regression designed to predict crown diameter, density and percent cover, from semivariance estimates, using computer simulated image series of four different species. Results show that the use of specific regression models significantly increase the general accuracy of the predictions. The identification of species using a per-pixel classification method remains a difficult task when applied to multispectral images similar to that of the announced smallsats (1 meter panchromatic and 4 meters multispectral).

Keywords: texture, semivariogram, structure, species, simulation, videography, smallsats, classification.

RÉSUMÉ

CARTOGRAPHIE DE LA STRUCTURE DES PEUPELEMENTS FORESTIERS PAR UNE APPROACHE TEXTURALE CONTRÔLÉE PAR L'ESPÈCE DOMINANTE

La texture visuelle des photographies aériennes renseigne les interprètes sur certaines caractéristiques structurales des peuplements forestiers. Les éléments texturaux peuvent également être évalués par le demi-semivariogramme directionnel mesuré sur des images numériques panchromatiques de 1 m de résolution. Toutefois, les relations mathématiques qui existent entre la texture des images et la structure du couvert forestier sont influencées par l'espèce dominante du peuplement. Nous avons évalué ces diverses relations à partir de régressions multiples servant à prédire le diamètre des couronnes, la densité et le pourcentage de couverture, à partir de la demi-variance, d'après des ensembles d'images simulées par ordinateur pour quatre espèces différentes. Les résultats montrent que l'application de modèles de régression spécifiques améliore significativement la qualité générale des prédictions. L'identification des espèces par une classification pixel-à-pixel demeurent toutefois problématique lorsqu'appliquée à des images multispectrales similaires à celles qui seront fournies par les *smallsats* (1 mètre en panchromatique ou 4 mètres en multibande).

INTRODUCTION

Estimation of forest stand structural parameters such as tree height, crown diameter, density, percent cover, and the like, can be carried out through remote sensing using methods that depend on the type imagery

that is employed: stereo-interpretation of aerial photos (Küchler, 1967), per-pixel statistical regression using multispectral low-resolution imagery (Franklin, 1986), computer textural measurements on high resolution imagery (Cohen et al. 1990; St-Onge and Cavayas, 1995), or automated crown delineation and counting, also on high resolution imagery (Gougeon, 1997). Despite intensive research in the field of digital forest mapping, nearly all forest maps at the stand level are still obtained through manual interpretation of stereo large-scale aerial images (approx. 1:15 000). Moreover, it is becoming increasingly difficult to find experts in traditional remote sensing due to the problems associated with the replacement of retiring photo-interpreters (Leckie, 1992). We believe that the textural approach to stand structure mapping offers a number of advantages that suggest that it could replace existing methods while increasing both precision and accuracy:

- computer measurements yield objective estimations impervious to manual interpretation bias,
- it has the potential for much more consistent results than the spectral approach, being based on the structure of the image instead of on the average reflectance of stands,
- it could be brought to an operational stage faster than the crown delineation approach because of its lower computational requirements, and since images having a resolution sufficient for textural measurement (but too low to allow crown delineation) are already available for large territories (e.g., RESURS 2 meter resolution Russian imagery).

Even though we are still awaiting a definitive definition of texture, visual analysis of texture has always been one of the most recommended criteria to characterise forest from aerial photographs (Spurr, 1960; Küchler, 1967; Howard, 1970). Methods that assess textural features, such as coarseness or "orientedness", by measuring some characteristics of the spatial distribution of grey levels over an image are numerous. Computer texture analysis has shown interesting results when applied to forest mapping in general (Atkinson and Danson, 1988; Cohen et al. 1990; Nel et al. 1994). We have recently confirmed the great potential of textural analysis for mapping stand structure (St-Onge and Cavayas, 1995) and delineating forest stands (St-Onge and Cavayas, 1997) that was foreseeable from previous studies (Yuan and Vlcek, 1989; Ryerd and Woodcock, 1990; Hay and Nieman, 1994; Kushwaha et al. 1994). Methods include simple local variance measures (Logan and Strahler, 1979), second order spatial statistics such as the co-occurrence matrix and the semivariogram (Cohen et al. 1990; St-Onge and Cavayas, 1995) and neural network approaches (Dreyer, 1993). Results in general show that texture measured at different scales reveal different informations: the mosaic of forest stands tends to influence texture on TM images (small scale mapping), giving an evaluation of the stand-to-stand variation, while light and dark patterns created by individual tree crowns allow within-stand evaluation of tree size or density (large scale mapping). It also appears that, in general, optical images contain more information than radar images and that second-order methods offer more information extraction potential than simpler statistics. However, indications from previous work show that tree species can alter image texture because of the variation in crown shapes, and thus in the projected shape of dark and light patterns corresponding to shadows and lit parts of the canopy, as well as the reflectance differences between species, that can in some cases create a polka-dot visual effect. This implies that consideration of stand species composition should be a part of the process of assessing forest stand structure using textural measurements if the operational stage is to be reached.

Our general objective is to develop an automated method for fine scale forest stand mapping using one and four meter resolution images from the "smallsats" (such as the ones announced by Orbview, Space Imaging, etc.). Targeted applications include 1:20 000 forest inventory, biodiversity/habitat studies, and the study of forest ecosystem processes. This implies that we need to identify, for each stand: species composition, mean height, mean crown diameter, density (stems per hectare) and percent cover (crown closure). The development and validation of the proposed forest mapping method comprises the following steps :

- Phase 1 –use simulated images to develop, train, and test algorithms,
- Phase 2 –apply and adjust algorithms developed in phase 1 to aerial images resampled to smallsat resolutions, and
- Phase 3 –apply and validate adjusted algorithms to high resolution imagery from smallsats when available.

This paper describes research activities related to the first phase of development.

STUDY REGION

Data and methods have been developed and tested for the *Training and Research Forest of Lake Duparquet* (TRFLD), an 80 square km of forested territory in the Abitibi region, Quebec (79.3 W, 48.5 N), which is part of the *Forest Ecosystem Research Network of Sites* (FERNS). This test area was chosen for its landscape and habitat diversity, representative of the mixed boreal forest, the wide availability of data, and the important collaborative effort between universities, forest companies and the socio-economic environment. Three research groups are presently conducting research projects in the area of the TRFLD totaling over 1 million dollars of investment: the GREF (*Groupe de Recherche en Écologie Forestière*) and the GEIGER (*Groupe d'Études Interdisciplinaires en Géographie et Environnement Régional*), both from Université du Québec à Montréal, and URDFAT (*Unité de Recherche et de Développement Forestier d'Abitibi-Témiscamingue*). Moreover, the TRFLD is managed by a mixed comity composed of two forest companies (Tembec and Norbord), hunting and fishing associations, the *Municipalité Régionale de Comté* (an administrative entity regrouping neighboring municipalities). This comity is also responsible of designing the management plan.

The forest landscape is essentially composed of hardwood, softwood and mixed stands aged from 50 to more than 230 years growing on a part of the Canadian shield culminating at 382 m. Common species include: Trembling aspen (*Populus tremuloides*), White spruce (*Picea glauca*), White birch (*Betula papyrifera*), Balsam fir (*Abies balsamea*), severely attacked by spruce budworm, Jack pine (*Pinus banksiana*), Eastern cedar (*Thuja occidentalis*), and Black spruce (*Picea mariana*). The study site was commercially exploited until 1992 and bears regeneration areas.

DATA

IMAGE DATA

Due to delays in smallsat launching schedule, an aerial survey was necessary to obtain adequate images of the study region. It was carried out by Air Focus (based in Chicoutimi, Québec) at the end of the summer of 1997. Bad weather made it impossible to obtain images during the growing season and postponed the flight to September 27th, date at which some of the deciduous trees had changed colour. A digitized airborne SuperVHS video camera mounted onboard a small airplane was used to acquire 26 flight lines, of approximately 25 images per line. Each image covers 742 by 543 50 cm pixels, yielding images of 371 by 272 meters, with approximately 10% overlap. The whole mission covers 27 km² at a cost of 1.85\$/ha (CAN). Detailed flight parameters are presented in Table 1. The digital images were produced by an analog to digital converter. Band-to-band registration post-processing was necessary to create sharp multispectral images (Figure 1). Preliminary simulation of smallsat images was carried out through band fusion and resampling. The one meter panchromatic band was created by averaging the green and red band on a pixel basis and resampling the resulting image by averaging the grey level values over squares of two by two 50 cm pixels (Figure 2), yielding a one meter band of 520 to 690 nm (with a gap of 30 nm between the two component bands). To create the multispectral 4 meter imagery, each of the original bands was resampled by averaging grey level values over a square of 8 by 8 pixels (Figure 3). No atmospheric or view angle radiometric corrections were performed at this stage. These images bear a high resemblance to the planned smallsat images because:

- they use CCD technology,
- they are composed of nearly identical spectral bands,
- the telephoto lens simulates near vertical view angles (5.3 degrees on each side of the nadir), and
- images are acquired in a snapshot mode, instead of a line scanning mode, which yields a high geometric quality, comparable to that of known satellite images.

There however exist some non negligible differences:

- the low flight altitude avoids the problem of significant path radiance over hundred of kilometres associated with space image acquisition,

- the CCD gain was adjusted for maximum contrast in forest environments, a feature that might not be available in smallsats, and
- some minor lens and angular effects have been observed in the aerial images.

Flight date: September 27, 1997

Flight time: 11h00 - 13h00

Sun elevation: 37 - 39 degrees

Flight altitude: 1890 m

Spatial resolution: 50 cm

Spectral bands (3 x 8 bits):

- green = 520 nm - 600 nm

- red = 630 nm - 690 nm

- infrared = 760 nm - 900 nm

Table 1. Flight parameters of the video aerial survey.

GROUND DATA

Ground data cut provided by the Training and Research Forest of Lake Duparquet includes height one-hectare plots where individual trees were mapped with a 25 cm precision and characterized for species, height class, DHP, and state (living/dead). These data have been geocoded and used to obtain spectral signatures for each tree species. Tree morphological data (height, crown diameter, length of living crown, crown ratio) used to calibrate geometrical models of trees used in computer image generation (section 4.1) was obtained for an average of 60 trees per species.

METHODS AND RESULTS

IMAGE SIMULATION

In this first phase, computer generated images were used instead of natural images to train the computer because of the impracticability of acquiring a real image-forest dataset, where the structure parameters of interest varied one at the time, and because of the high costs of *in situ* forest measurements. The 0.5 metre multispectral images were generated from three dimensional computer models of trees as described in St-Onge and Cavayas (1995). Illumination was simulated by parallel rays and shadows were calculated from the 3-D model (tree shadows cast on the ground and on other trees). The trees were modelled by symmetrical functions, giving rise to shapes similar to hardwood (ellipsoids) and softwood (bullet shape) crown envelopes placed on sticks representing the bole (Figure 4). The reflectance of the background or understory and of the tree crowns were obtained by sampling the aerial video images. The sampling of tree crowns was carried out in a way that all sample trees were located in the same flight line to enforce constant sun elevation and azimuth, and thus constant configuration of the lit and shadowed parts of the crowns. The simulation algorithm comprises the following steps:

- 1) The multispectral background sample is placed in the three reflectance layers (corresponding to the three spectral bands).
- 2) Three-dimensional trees are "planted" in the geometrical layer according to a random process generating *x,y* coordinates constrained by a minimum distance between any two tree stems (Strauss process) and a statistical distribution of heights and crown diameters (Weibull distribution).
- 3) Crown reflectance patterns sampled in the video locally replace background reflectances in location corresponding to tree crowns placed in the preceding step. Crown reflectance patterns are scaled to the diameter of the geometrical crown by nearest-neighbour resampling.
- 4) Shadows are calculated for a sun elevation (38 degrees) and azimuth (225 degrees N) identical to that of the sampled flight line. The spatial extent of the shadows projected on the ground and on other trees are placed in a shadow layer.

- 5) Each pixel of the reflectance layers falling in the marked areas of the shadow layer are divided by a constant corresponding to the ratio of lit to shadowed part of the canopy calculated for each spectral band of the aerial video images, thus simulating both crown transparency and sky irradiance effects.
- 6) Band fusion and resampling is carried out using the procedure described in the preceding section concerning image data.

This geometrical-optical simulation procedure produces realistic images having textural characteristics very close to those of similar natural images (Figure 5).

THE SEMIVARIOGRAM

The texture measure used for stand structure evaluation is founded on the semivariogram, which measures the average difference between pixels separated by lag h , given in pixels or directly in ground meters:

$$2\gamma(h) = E[f(x+h) - f(x)]^2 \quad (1)$$

It has the following characteristics and advantages: a) the measure relies on a very limited set of assumptions in comparison to those of the autocorrelation function or Fourier transform (Ramstein and Raffy, 1989); b) it is not tied to the choice of initial parameters such as relative position of the pixels and the matrix analysis method (contrast, entropy) needed to control co-occurrence algorithms; and lastly, c) it yields texture values directly in terrain distance units. It is also impervious to variation of contrast in the image such as those produced by sensor gain, emulsion speed or atmospheric attenuation (St-Onge, 1994). The semivariogram has been used in the past to estimate the optimal window sizes for texture or spectral measures in natural forest or plantations (Atkinson and Danson, 1988; Franklin and McDermid, 1994), to assess tree damage (Franklin et al. 1992) and to estimate stand structure parameters (Jupp et al. 1988; Woodcock et al. 1988).

The typical semivariogram exhibits a rise that gradually slows to form a straight horizontal line (sill) due to the fact that increasing the distance between two pixels augments the chance of observing a great difference between their values but, after a certain threshold, the lag increase does not result in any more difference (Figure 1b). The height of the sill is normally proportional to the global image variance while the lag at which the sill is attained, called the "range", is generally a very good indicator of texture coarseness. The semivariogram can be calculated along transects (Atkinson and Danson, 1988; Ramstein and Raffy, 1989) but gives a better representation when calculated in more than one direction (Cohen, et al. 1990; Woodcock et al. 1988) because texture is in many cases anisotropic (Davis, 1981). The texture measure presented here was composed of three values given in ground meters: the range of the semivariogram in the direction parallel to the sun rays at the moment of image acquisition, a_{par} , the range in the perpendicular direction, a_{per} , and the range in the intermediate direction (45 degrees from both parallel and perpendicular directions), a_{mid} . These individually characterize texture coarseness in different directions and, together, estimate texture anisotropy. Each value is obtained by calculating the semivariogram, usually referred to as "the experimental semivariogram", in one given direction and then by adjusting a two parameter function, in our case the spherical model (see for example Curran, 1988) characterized by the range, a , and the sill, c , on the experimental semivariogram by least square fitting. The details of semivariogram estimation are presented in St-Onge and Cavayas (1995). We emphasize the fact that first-order statistics of the image are completely left out by the texture measure, in other words, the average reflectance of a forest stand or the global variance of the digital values corresponding to the image of a given stand do not participate significantly in the texture scores.

PREDICTING STAND STRUCTURE PARAMETERS

Predicting stand structure parameters was done by using a set of three functions relating the texture parameters to the structure parameters. These functions were derived from a multiple regression analysis having a_{par} , a_{per} and a_{mid} as independent variables and crown diameter, CD , stand density, SD and crown closure CC , successively as dependent variables. Average stand height was left out because previous work indicated that height does not have a strong direct relation with image texture, and since it can be derived from crown diameter through allometric equations. The multiple regression analysis was run on a dataset composed

of 120 computer generated images (Figure 6), i.e., 30 images for each of the following species: jack pine, trembling aspen, white birch and white spruce. Minimum and maximum stand structure values used in the simulations appear in Table 2. General prediction models were calculated using stepwise regression for the whole 120 image dataset. The same procedure was applied to each of the four species image subsets. Coefficients of determination (R^2) of each model are presented in Table 3. R^2 range from 0.67 to 0.71 in the case of the general model. Prediction efficiency was significantly increased when regression was performed on a species by species basis: R^2 then reached 0.80 and 0.82 in the case respectively of crown diameter and density. Percent cover coefficient of determination, however, remained at a rather low level of 0.69, a fact that can theoretically be alleviated by predicting this parameter using the two others.

Species	Image set 1	Image set 2	Image set 3	Image set 4
Jack pine	10 m – 500 t/ha	10 m – 1000 t/ha	15 m – 500 t/ha	15 m – 1000 t/ha
Trembling aspen	15 m – 1000 t/ha	15 m – 2000 t/ha	20 m – 1000 t/ha	25 m – 1000 t/ha
White birch	15 m – 500 t/ha	15 m – 1000 t/ha	20 m – 500 t/ha	20 m – 1000 t/ha
White spruce	15 m – 1000 t/ha	15 m – 2000 t/ha	20 m – 1000 t/ha	25 m – 1000 t/ha

Table 2. Values of average height and density used for each species in the computer image simulations (height in metres – density in tree/hectare).

General model	Species corrected Model
CD $r^2 = 0.71$	$r^2 = 0.80$
D $r^2 = 0.67$	$r^2 = 0.82$
PC $r^2 = 0.69$	$r^2 = 0.69$

Table 3. Resulting R^2 for the general and species corrected models for crown diameter (CD), density (D) and percent cover (PC). All R^2 are significant to $F=0.001$.

IDENTIFICATION OF TREE SPECIES

The above-mentioned results suggest that prediction accuracy of stand structure parameters generally increases when regressions models are calculated for each species, which brings about the corollary task of identifying tree species using remote sensing means. Preliminary classification was attempted to evaluate the performance of the standard per-pixel maximum likelihood method. The procedure consisted in 1) acquiring spectral signatures corresponding to the "purest" parts of the lit crown of each tree species, as well as of shadows and understory, 2) classifying the images, 3) calculating the percentage of area covered by each class in the images resulting from step 2, and 4) choosing the species corresponding to highest percentage. While classification of the raw 0.5 meter resolution multispectral aerial video imagery yielded very good results (to be published), lower resolution images as the ones that are expected from the smallsats (approximately 4 meter in the multispectral mode), or one meter panchromatic imagery, did not offer sufficient information to allow an acceptable level of correct identification. One meter resolution multispectral images obtained by merging the one meter panchromatic to the four meter multispectral imagery, or by directly degrading the 0.5 meter multispectral also gave unreliable results. Table 4 shows the distribution of percentages for computer simulated images of varying species and structure for the latter type of imagery. We can observe that when the crown

coverage is very high (highest values for both height and density), the correct species was found in most cases. However, lower coverages yield unreliable results.

<i>Simulation parameter values</i>			<i>Predicted values (% area)</i>						
Species	Height	Density	Pb	Pt	Bp	Pg	Shade	Backg d	Unclassifie d
Pb	10	500	3.56	0.71	0	0	36.89	34.28	24.56
Pb	10	1000	0.88	0	0.22	0	22.02	23.97	52.91
Pb	15	500	1.34	0	0.46	0.02	25.05	19.97	53.15
Pb	15	1000	18.99	0.05	14.18	0.1	14.62	22.88	29.17
Pt	15	1000	8.52	19.41	2.66	0	24.44	31.3	13.67
Pt	15	2000	4	50.2	0	0	13.62	24.71	7.47
Pt	20	1000	24.83	3.25	22.78	0	10.13	18.16	20.85
Pt	25	1000	2.88	59.62	0	0	14.23	18.48	4.79
Bp	15	500	2.91	0.1	0.15	0	43.92	33.57	19.36
Bp	15	1000	9.72	0.93	0.07	0.05	14.87	27.49	46.88
Bp	20	500	1.39	0	0.07	0	16.06	27.61	54.86
Bp	20	1000	12.55	0	40.5	0.07	2.56	9.06	35.25
Pg	15	1000	1.25	0.02	0.1	0	29.13	23.95	45.56
Pg	15	2000	3.74	0	2.34	0.02	14.65	30.3	48.95
Pg	20	1000	0.49	0	1.15	0	9.01	15.8	73.56
Pg	25	1000	4.25	0	6.69	0	15.36	20.34	53.37

Table 4.

DISCUSSION

Crown diameter and density prediction accuracy reach levels ($R^2 > 0.80$) that could allow considering this method as an operational candidate. Such high coefficient of determination for small ranges of height and density (e.g. differences respectively as low as 5 m and 500 trees/ha for pine and birch image series) are indeed encouraging. However, the shape of the crown, and the average crown ratio, believed to be the main factors affecting the relationship between stand structure and image semivariance, must be taken into account. They affect the size of light and dark patterns visible on the images for a given crown diameter and stand density, as well as the "orientedness" of texture: slim pointy crowns let more light reach the understory and thus create elongated patterns along the direction of lighting. It follows that different statistical models are necessary for predicting structural parameters for each species and most probably for mixed stands of various proportions. Choosing the right model is complicated by the fact that species must be identified prior to assessment of stand structure, a task that cannot be successfully carried out by standard per-pixel classification. This approach indeed relies on spectral signatures of individual crowns, which is a useful indicator of tree species when the pixel size is significantly smaller than the lit part of the crown, but is unworkable when that size increases over a given threshold. Results suggest that even 1 meter pixels are often too wide to capture "pure" crown signatures, being mixed with shadowed crown or background. Furthermore, at resolution between 1 and 4 meters, the "purity" of pixel is influenced for a given species by the three-dimensional structure of the canopy, pure pixels being more probable in high coverage stands of trees with large crowns. Degrading the resolution to a point where a pixel integrates the reflectance of multiple crowns would generate imagery comparable to that produced by lower resolution sensors, such as SPOT-HRV or Landsat-Thematic Mapper, and in which case reflectance depends on species composition as well as on structure, preventing precision assessment of both aspects. We believe that local histograms, or spectral unmixing techniques, might yield better results, especially if an initial rough estimate of tree size and density can be produced. Furthermore, a relaxation

process could be employed to successively refine species identification and structure assessment in an iterative way.

CONCLUSIONS

The current study, based on computer simulated images of 1 and 4 meter imagery, yielded the following conclusions:

- structural forest stand parameters, such as crown diameter and density, can be successfully estimated using one meter image semivariance, even for relatively small size or density increments;
- estimates are significantly more accurate when models calibrated for each species are used; it follows that an operational method would have to take species into account, and rely on accurate species composition information; and
- species identification from 1 - 4 meter resolution images using per-pixel maximum likelihood classification yielded unreliable results and other processing means will have to be employed.

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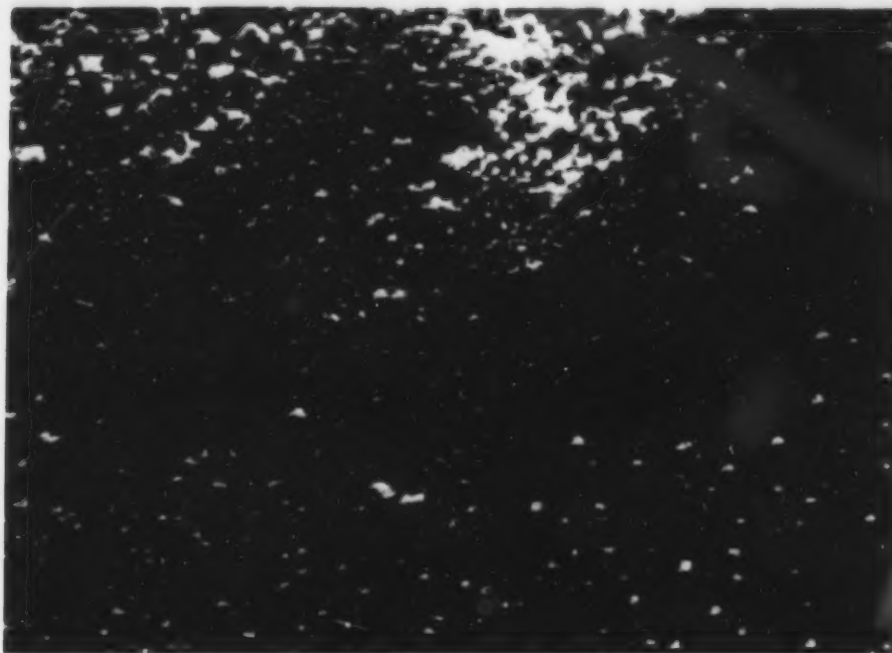


Figure 1. Various tones and texture show the complexity of the forest mosaic of the study region on 0.5 meter multispectral raw aerial video.



Figure 2. One-meter panchromatic imagery simulated by resampling and merging initial green and red bands.

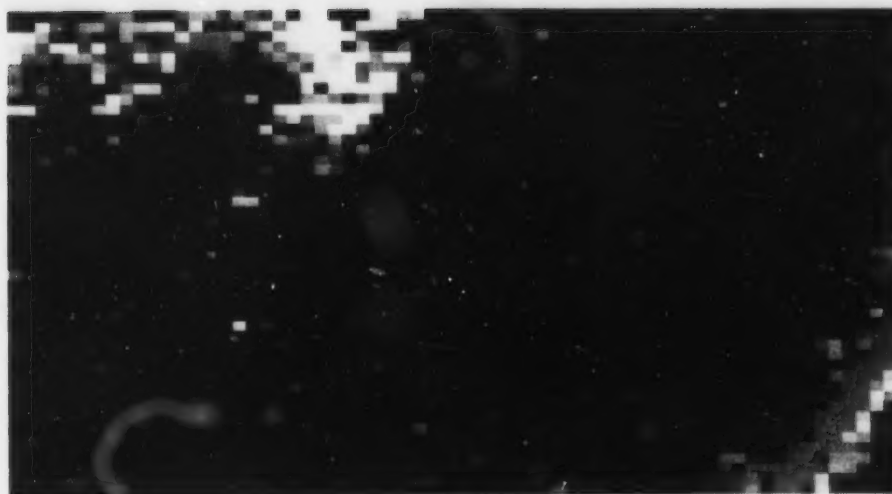


Figure 3. Four-meter panchromatic imagery simulated by resampling the three initial spectral bands.

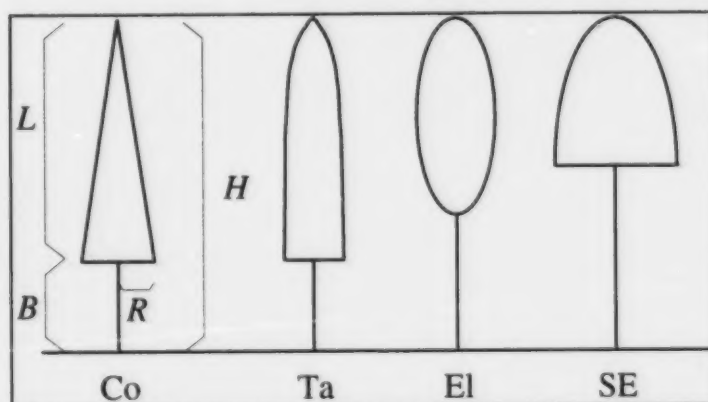


Figure 4. Basic tree geometrical models used in the stand image simulations.

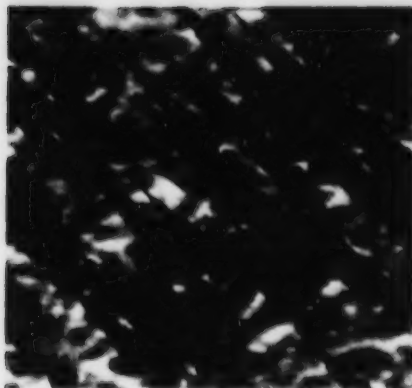


Figure 5. Example of a 0.5 meter image resulting from the computer simulation process.

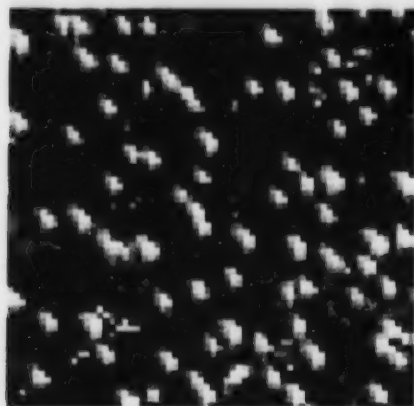


Figure 6. Example of a 1 meter panchromatic image resulting from the computer simulation process.

Computer-assisted Interpretation Systems



COMPUTER-ASSISTED PHOTOINTERPRETATION AIDS TO FOREST INVENTORY MAPPING: SOME POSSIBLE APPROACHES

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ABSTRACT

Aerial photointerpretation is the mainstay of management forest inventories. Accuracy and consistency of this interpretation is a major concern. In addition there is a growing demand for these inventories to provide more quantitative information and data on new forest parameters. Incorporation of computer-assisted techniques to the interpretation process offers potential to improve forest inventories along these fronts.

Techniques must fit into the current infrastructure of mainly small or independent interpreter groups or individuals using 1:10 000 to 1:20 000 scale stereo photography. Computer-assisted interpretation therefore must be based on digitized photography and not necessitate large computers or costly display systems or analysis software. They must be simple to apply and not require inordinate fine tuning or trial and error by the interpreter.

Envisaged techniques are: 1) computer-based interpretation keys, 2) recall and display of ancillary data, 3) computer-assisted interpretation review where interpreters can quickly compare all stands they have interpreted as a given stand type, 4) automated single tree analysis including automated single tree isolation, delineation and species classification, plus estimations of stems/ha, crown closure, crown size, numbers of snags, and gap or patch size distribution, and 5) pixel and area based features such as conventional pixel classification and various texture measures for stands that could be presented visually or numerically to the interpreter as an aid. As well, visual or parametric comparison of current and past inventory photography presents a vast array of possible benefits to interpretation.

Keywords: forest inventory, photointerpretation, remote sensing, image analysis.

RÉSUMÉ

AIDES À LA PHOTO-INTERPRÉTATION ASSISTÉE PAR ORDINATEUR APPLIQUÉE À LA CARTOGRAPHIE DES INVENTAIRES FORESTIERS: DES APPROCHES À ENVISAGER

La réalisation des inventaires forestiers repose en grande partie sur l'interprétation des photos aériennes, laquelle doit être menée avec un degré de précision et d'uniformité élevé. En outre, on espère pouvoir tirer de ces inventaires de plus en plus d'informations quantitatives et de données sur de nouveaux paramètres

forestiers. Dans ce contexte, l'intégration de techniques d'analyse assistée par ordinateur au procédé d'interprétation offre des possibilités intéressantes pour l'amélioration des inventaires forestiers.

Les techniques envisagées doivent pouvoir s'harmoniser à l'infrastructure actuellement utilisée par les groupes, principalement restreints ou indépendants, d'interprètes ou les individus qui travaillent avec des photos stéréoscopiques prises à une échelle variant entre 1/10 000 et 1/20 000. Par conséquent, la photo-interprétation assistée par ordinateur doit se fonder sur la photographie numérisée et doit pouvoir être réalisée sur de petits ordinateurs à l'aide de systèmes de visualisation et de logiciels d'analyse peu coûteux. Ces techniques doivent être faciles à appliquer et nécessiter un minimum de réglage fin ou de tâtonnements de la part de l'interprète.

Parmi les techniques envisagées, citons : 1) les clés d'interprétation par ordinateur, 2) le rappel et l'affichage de données auxiliaires, 3) l'examen de l'interprétation assistée par ordinateur, permettant aux interprètes de comparer rapidement tous les types de peuplements identifiés, 4) l'analyse automatisée d'arbres individuels, y compris l'isolation et la délimitation automatisées d'arbres, la classification des espèces, l'évaluation du nombre de tiges/hectare, la fermeture du couvert, la dimension du couvert, le nombre de chicots, la répartition des trouées ou des vides par superficie et 5) les fonctions d'analyse par pixel ou par zone, notamment la classification classique par pixel, et diverses mesures de texture des peuplements, présentées visuellement ou numériquement, en tant qu'aides à la photo-interprétation. De plus, la comparaison visuelle ou paramétrique des photos d'inventaires récentes et passées offre de nombreux avantages pour la photo-interprétation.

INTRODUCTION

Air photo interpretation is a basis of most management forest inventories. Stand delineation is a major component. For designation of stand attributes, accuracy, consistency, speed/cost, and level of detail are key factors. In addition, an ability to quantify interpretations to a finer level of detail (precision) and interpret new parameters is becoming increasingly important. There is a growing diversity of issues being addressed in forest management and urgency to make correct management decisions. A consequence is a need for more accurate information on the forest environment and for a much wider suite of data to be available. There would be interest among forest managers and inventory specialists in utilizing new techniques that would meet these demands in a cost effective manner. Automating some of the photointerpretation process and/or providing digital products to aid interpretation is a possible way of improving the effectiveness of an inventory. Recent developments in computer technology (especially reasonable cost display and storage capabilities), digital imagers, digitized photography and computer image analysis techniques make this possibility worth pursuing.

The general approach to developing computer-assisted interpretation aids, at least in the early stages, should be pragmatic. The simple objective should be to add tools that will help the interpreter, not replace any of their function. Expectation should not necessarily be to provide universally similar and correct parameters from the automated systems, just something that is useful and can be easily detected as poor when it does go awry. Initially quite a number of possible methods will have to be explored. Close interaction and suggestions from interpreters is essential. As these are vetted, more scientifically rigorous examination of the methods and results would be conducted. Techniques must fit well into the operational setting where they will be used. In the end, it is hoped that a suite of data processing and analysis techniques would be developed and available to the interpreter to use as they see fit. These would be applied to digitized photographs either by the interpreter groups or centrally. The interpreter would be presented results visually on the computer screen as layers on top of the imagery itself. This would augment the interpretation which may also be done on the screen or more likely on photographic prints of stereo pairs. For certain parameters such as crown closure, the quantitative information from the automated method could be incorporated as the final attribute. Special parameters such as the distribution of canopy gaps (openings) could be extracted at this time or later as needed.

This paper discusses the operational setting into which computer-assisted methods must fit and the consequences of these on system designs. The pros and cons of various general approaches are examined (e.g., single tree interpretation, traditional pixel-based classification, area based techniques, change detection,

interpretation keys, review of interpreted stands and ancillary data display). Speculations are presented on expected capabilities and difficulties.

OPERATIONAL SETTING AND CONSIDERATIONS

Any techniques developed must be appropriate to the environment where they will be used. This discussion deals mainly with large inventory mapping projects. It must also be recognized that there is significant amounts of site specific and special purpose interpretation done outside the main inventory mapping environment.

Forest inventory is usually managed by government forest agencies or larger forest companies. Interpretation can be done by in-house experts, but more often than not it is done on contract usually by individuals or small companies. Since the interpretation must be digitized and input into a GIS, there is computer technology and expertise in the production loop. However, there is generally not a large technological infrastructure in place. In addition, the process of photointerpretation is time consuming and a significant cost component of inventory mapping at around 25% (Leckie and Gillis, 1995). As a consequence of this environment, automated interpretation solutions cannot necessitate large computer or costly display systems for the interpreter. They must also be simple and quick to apply, demand little training or additional specialized expertise and not require a lot of fine tuning or trial and error by the interpreter.

Stereo aerial photography at scales of 1:10 000 to 1:20 000 is the mainstay of management inventory. Much of this is black and white photography, although normal colour and colour infrared are not uncommon. At this time there are no other sensors available that can fulfill the full needs of management inventories. Therefore, digitized air photos near this scale must be a significant focus for computer-assisted photointerpretation systems. The absence of multispectral data on B&W photos and at best moderate quality (radiometrically and spectrally) multispectral information from colour films limits the analysis options. For example, species discrimination using spectral data alone especially on B&W photography will be limited. This context does not negate the value in developing systems based on digital multispectral imagery, but indicates that to receive widespread adoption in the current environment they must also be adaptable to get useful information from aerial photography.

Another factor is the quantity of data. Over the areas involved in large inventory projects, data volumes are enormous. For digitized photography, the quantity of digital data depends on the resolution of the digitization. There are useful methods to assist interpretation at lower resolutions 1-3 m, but more sophisticated techniques can utilize high resolution to good benefit. It is the authors' belief that there is good reason, in terms of information content and interpretability, why inventory mapping has evolved to use 1:10 000 to 1:20 000 photography. To maintain the spatial detail of these photos, equivalent resolutions for digital imagery are 15 to 40 cm (Leckie, 1990), and Leckie(1993) showed that 70 cm data was sufficient for interpretation of digital multispectral imagery of a test site in Ontario. Therefore, digitizing in the order of 50 cm is a reasonable assumption for this discussion. Although the total volume of data is large the actual amount an interpreter views at one time is not. Generally 5 to 15 photos are interpreted per day. Reducing this to typical values, interpretation rates are roughly one photo per hour, 400 new hectares and 10 to 15 stands in an hour (Leckie, 1989; data of Leckie and Gillis, 1995). This does not put a strain on modern computer capabilities. Running some of the needed analysis algorithms over large areas is computer intensive, but, since the interpreter does not interpret large areas at a time or within one day, the processing load is almost assuredly amenable to preprocessing on small computers. It however should be noted that if one takes a typical high scan rate of most high-end digitizers (e.g., 7.5 microns which produces an approximately 11 cm pixel size for 1:15 000 scale photographs), a 30 000 by 30 000 pixel image is created and does result in significant processing requirements.

However, for a full interpretation capability "screen real estate" is an important issue. If one wants to duplicate the area seen on a photograph (assuming a 50 cm resolution) a screen of 7000x7000 would be needed. For say 400 ha of new land interpreted on each photo, the screen size is still problematic at (4000x4000). Even an 100 ha stand, which is a large stand but not unusual, needs a display over 2000x2000 pixels. In reality, the interpreter wants to see much more area than this to give context. Well thought out zoom, decimate, overview and double screen (dual monitor) systems need to be considered. Fortunately, in the computer-assisted

interpretation application, "full out on-screen interpretation" is not necessary. Display of segments of a scene is sufficient. Regardless, screen real estate and manipulation is a major design factor. Stereo viewing of the data is essential for interpretation. This can be accomplished by stereo viewing of the paper prints of the photos as is traditionally done. However, display of stereo digital imagery for the computer-assisted methods is desirable but not absolutely necessary. There are various methods for displaying stereo imagery on a computer screen, each with pros and cons. None, however, precisely fits the need of full interpretation. Screen "real estate" is an even bigger issue for stereo display.

A key advantage in developing and implementing computer-assisted interpretation versus full interpretation systems is that a whole interpretation system does not need to be implemented at one time for it to be operationally useful. There is a good probability of success with incremental implementation of methods within the limitations of the setting.

ENVISAGED APPROACHES

This section describes possible general approaches and example suites of new interpretation aids and procedures. The operational framework consists of the following. The 1:15 000 scale inventory photography would be digitized to at least 1 m resolution. Interpretation would be done on the paper print photographs in stereo, but assisted by several types of computer based tools. Processing for these tools would be applied to the digitized photographs, most likely centrally, prior to interpretation. The interpreter would display results visually on the computer screen as layers on top of the imagery itself or on simple mylar overlays over the air photo prints. Parameters such as crown closure, gap distribution, number of snags and crown sizes could be extracted at this time as an aid to interpretation or later as needed. These tools will be integrated with on-screen interpretation as it comes into use. The types of tools can be categorized into six categories (1) computer-based interpretation keys, 2) recall and display of ancillary data, 3) computer-assisted interpretation review, 4) automated single tree analysis, 5) pixel and area based techniques, and 6) change detection. The first three essentially display example or ancillary data, the latter three analyze the imagery and provide the interpreter with quantitative data or relevant derived patterns in the imagery.

COMPUTER-BASED INTERPRETATION KEYS

Computer-based interpretation keys could be considered an on-line version of an interpretation manual. Examples of stand types and rules for resolving among difficult to interpret species would be stressed. Dichotomous, selective or elimination keys would be used. Elimination keys are useful to interpreters. They eliminate possibilities based on photointerpretation elements or contextual information such as ecological setting. One option for these keys would be within an expert system structure. The main advantage of the computer-based interpretation keys would be in ease of use. They are of most value in training or for inexperienced interpreters. Experienced interpreters rarely use keys.

RECALL AND DISPLAY OF ANCILLARY DATA

Imagery would be referenced to existing data, such as the previous inventory map and stand attributes, history records of disturbance or silvicultural activities, any ground plots or observations, and key information such as elevation and ecological zone. The interpreter could recall and display this information over the digitized photography on screen. A key component might be example images easily accessed from an on-line library and displayed on a computer screen. This would include digitized representative images based on a variety of source data. For example, image chips around all stands known to be of a certain type via various field plots and visits. Ground photos for the field sites could be digitized, georeferenced and displayed. Large scale photographs of stands of that type could also be displayed when available. Eventually, other information such as that from airborne laser height estimation systems could be incorporated. As well, the old inventory photography could be digitized and displayed alongside an image of the same stand from the current inventory photography. The interpreter could better judge whether the stand has fundamentally changed and better utilize the old stand parameters in the new interpretation. These types of techniques could prove very useful in keeping the interpreter calibrated, accurate and consistent.

COMPUTER-ASSISTED INTERPRETATION REVIEW

The functionality of computer-assisted interpretation review would include capabilities to query and display concurrently all stands already interpreted as a given type. The interpreter could compare these stands and quickly identify anomalous interpretations. Use of stereo systems and techniques could be incorporated for viewing the stands on the screen. One could also envisage using comparisons of image based parameters (derived by the methods described below) among these stands to automatically identify potential outliers and questionable interpretations. This could considerably enhance consistency of interpretation and may indeed be the simplest but most powerful computer-assisted tool. There is, however, a logistical issue with this application. It implies that the interpretation (delineation and attributes), ostensibly on the paper version of the photograph, are routinely digitized and input into a database for access by the system.

AUTOMATED SINGLE TREE ANALYSIS

Automated single tree analysis is suitable only for high resolution imagery of approximately 1m meter or less. Algorithms would identify the presence of a tree, delineate its crown, and try to establish its species (Barbezat and Jacot, 1998; Brandtberg, 1998; Culvenor et al., 1998; Dralle and Rudemo, 1997; Dubé et al., 1998; Gougeon et al., 1998; Key et al., 1998; Larsen, 1998; Niemann and Adams, 1998; Pinz, 1998; Warner et al., 1998; Pollock, 1998). Additional information regarding its health may be extractable. In addition to spectral information, other image parameters used by photointerpreters could be algorithmically/mathematically expressed and used in automated methods (e.g., crown outline shape, branching structure, texture, etc.). Context information such as elevation and ecological setting extracted from various data bases could also be used for species determination. Automated single tree methods would also provide information on the distribution of stems, crown size, crown closure and gaps. Results could be presented visually or quantitatively to help the interpreter. Images of stand attributes such as crown closure could be displayed to aid interpretation (e.g., Figure 1). An important fact to remember is that these computer based methods are only being used to aid the interpreter with additional information. Certainly at this stage of development of automated interpretation it is not meant as the primary source of information and may often have to be ignored. Nevertheless, it may show some subtleties not identified by the interpreter or indeed provide quantitative attributes deemed suitable by the interpreter to use as the stand description. If producing good results the stand description will often be more precise than that which the interpreter could provide. Crown closure, species composition and if required stems/ha would be examples. In aspects of this application, again there is a logistics problem. If the interpreter wants a summary of the automatically derived stand parameters, it implies that the stand boundary just interpreted is digitized and georeferenced to the automatically interpreted image. As well, the interpreter is using the information provided to help delineate stand boundaries. Summaries on a stand basis to help this process cannot be generated until the boundary is determined. Automated segmentation or stand delineation can be incorporated as an aspect of the process.

The automated analysis, if deemed satisfactory by the interpreter, can lead to a new set of possible or optional attributes not necessarily mandated in the inventory (e.g., stems/ha, stand gap size distribution, numbers of snags or large trees, or crown size distribution). As well, stand delineation based on species composition, crown closure, gap sizes, and or stems/ha can be generated automatically (Gougeon, 1997). Other environmental strata based on the forest conditions needed, say, for nesting of a given important bird, can also be compiled.

PIXEL AND AREA BASED TECHNIQUES

Traditional pixel based image classification techniques are best applied on medium and low resolution data; they generally do not perform well with high resolution data. At lower resolution there are many mixed pixels of tree and stand components (e.g., sunlit or shaded trees and open areas, different species). They will be problematic in consistently providing stand attributes appropriate for management inventories. Exceptions would be simple uniform single species units. It also must be remembered that, for the most part, systems will be analyzing only panchromatic or low quality multispectral data from aerial photos. Such techniques, whether applied to low or high resolution data, may, however, provide patterns of forest vegetation useful to the interpreter at a secondary level. For example, one could match the texture, Fourier Transform or variogram of a stand to that of a known stand of a known density to estimate stand density. Area-based characteristics such as

texture and other image parameters based on the basic photointerpretation elements could be calculated. The techniques are best used if stands are already delineated. They can be applied without this requisite, for example, areas of homogeneous image parameters such as texture could be automatically outlined and presented to the interpreter. Again the interpreter could use both pixel based classifications and area based parameters as a visual aid to objectively recognize similar interpretation elements or to statistically match the parameters of different stands to identify potentially similar stands.

Because of the large number of component parts of a forest stand that contribute to its overall reflectance pattern and innumerable ways they can be arranged, pixel and area based analysis techniques have generally not met with success over anything but select conditions. A stand with the same inventory attributes can have a wide variety of possible reflectance characteristics and patterns. A given set of spectral characteristics can result from different stand types. However, there are possibly area based methods that could provide information or patterns useful for interpretation. As well, because the human interpreter is controlling decisions, a method is valuable even if it helps only occasionally or only differentiates one specific problem condition.

CHANGE DETECTION

Having previous and current images, plus the interpretation from the past inventory expands the number of possible computer-assisted techniques. It requires that both sets of photography be digitized and massaged. It is expected that benefit could come from comparing image parameters or automated single tree results from an image taken say at the time of the last inventory with current inventory image parameters. If these parameters have not changed then it can be assumed the stand has not fundamentally changed and use the old inventory attributes (grown over time) would be appropriate. The old stand boundary could also be used leading to potentially very significant efficiency gains. Digitizing of stand boundaries is a major cost of an inventory (Leckie and Gillis, 1995). One could also build a projection of what the image parameters would look like under normal stand development over the time period and compare current parameters to expected image parameters. Where there is change detected, other automated interpretation techniques could be used or a comparison made of image parameters with those expected under a given change. Of course, these methods gain most benefit when there is confidence in the previous inventory. It is not anticipated that registration between images would, under normal circumstances, be sufficient to conduct tree for tree comparisons, but area based change detection techniques would be useful.

It should also be noted that with such change detection methods a whole new inventory approach is possible. Change detection techniques would be used to determine areas that have undergone changes beyond normal stand development. Only these areas would actually be interpreted by the photointerpreters, vastly reducing the interpretation task. Digitizing and analyzing the photography from the previous inventory is onerous but if one does an automated interpretation on the new inventory, it would be available to use with the next inventory interpretation, be it a new inventory cycle or an update.

CONCLUSION

The goal of computer-assisted interpretation methods should be to improve the inventory in terms of quality, add additional quantitative parameters and do this at little or negative cost impact without significantly altering the current framework of inventory production. The methods, although having sophisticated underpinnings, therefore, should be designed to be used with minimal computer equipment (e.g., PCs) and computer expertise. They should be based on using digitized 1:10 000 to 1:20 000 B&W, normal colour or colour infrared photographs, while still recognizing that fully digital systems are gradually becoming an increasingly viable option for some applications. These requirements are based on the current operational setting and state of relevant technologies. They will all evolve together over time. In addition, this paper has discussed the computer based techniques in terms of 'assisting' the interpreter. As methods are developed and become mature, one must recognize the potential role of such techniques to provide spatially explicit quantitative information that can be compiled not only on a traditional stand basis but into spatial units to meet specific forest management needs. For example, the habitat for an important bird species, or presence of trees

of a specific species and size. The role for providing data on new types of information not traditionally interpreted will also be important.

Use of on-line interpretation keys and ready access to ancillary data can only improve interpretation quality. The development of tools for the interpreter to review the appearance and image characteristics of stands he/she has interpreted as having similar attributes may prove the most beneficial of all computer-assisted interpretation tools. Automated single tree analysis should prove useful for identifying trees, tree sizes, crown closure, snags and gap distribution. For black and white and even colour photography the spectral information regarding species composition will be weak, but digitization at very high densities will permit structural and textural parameters to be used effectively in automated species estimation. For pixel and area based analysis methods, the approach should be less quantitative and more towards providing "clues" or "patterns" potentially useful to the interpreter, for example, highlighting areas with similar spectral content or texture. The interpreter can then determine if the areas are meaningful and add insight into the interpretation. Alternately, the system could tell the interpreter "this area or stand matches the texture pattern expected of, say, dense, mature lodgepole pine or open ponderosa pine, etc.". As well, one could match the texture, wavelet transform or variogram of a stand to that of a stand of a known density to estimate stand density. These techniques are best used if stands are already delineated but can be applied without this requisite. Development of useful area based techniques may prove problematic as stands of similar stand attributes can have quite different spectral and textural characteristics. However, the intent of the computer-assisted approaches outlined is not to provide stand alone methods but simple tools to assist the interpreter. Therefore, it is anticipated that effective area based parameters will be developed. A key immediate benefit of change detection techniques would be an efficient mechanism to identify stands with no unexpected change or boundary alteration, and thus permit the adoption of the old stand boundary, eliminating the necessity of full digitizing of all stand boundaries (an extremely costly component of an inventory). Change detection techniques will likely be the last to be developed and implemented but perhaps offer the greatest potential impact on inventory procedures.

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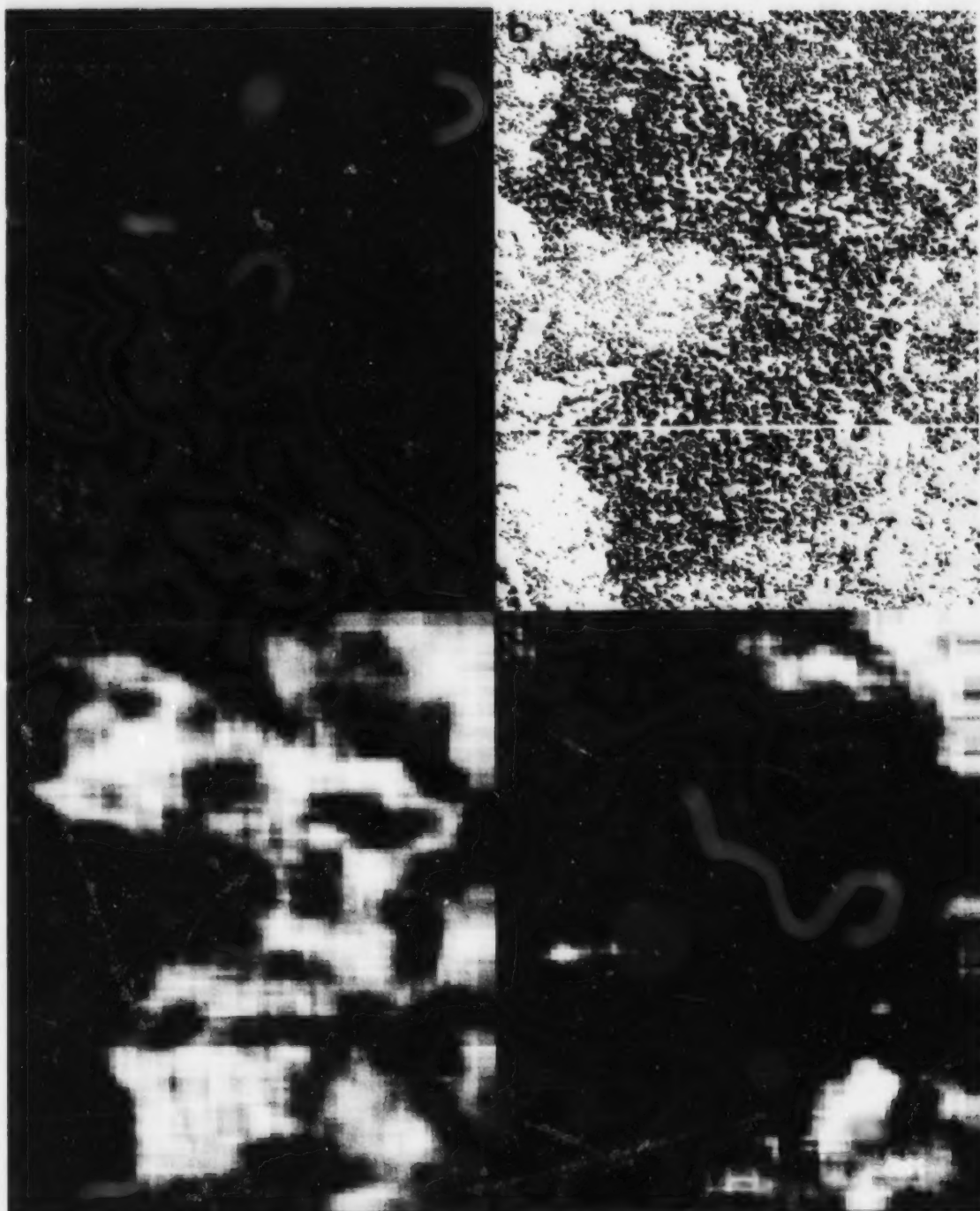


Figure 1. Digitized 1:19 000 scale colour infrared aerial photograph (60 cm resolution) and derived parameters. The area consists of a mature Douglas fir, Hemlock, Cedar stand surrounded by regeneration. a) Digitized photography, b) isolated trees with ITCISOL (Gougeon, 1998) classified into 6 species, c) crown closure image (high intensity equals high crown closure), d) stems/ha image (high intensity equals high stems/ha). (data provided by MacMillan Bloedel Ltd.).



THE CLAPA PROJECT: AUTOMATED CLASSIFICATION OF FOREST WITH AERIAL PHOTOGRAPHS

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ABSTRACT

Software has been developed which meets the needs of foresters and runs on a PC or Macintosh computer. The approach adopted is one generally used in microengineering production. The software enables trees, groups of trees and dense forest to be recognised on different types of digitized aerial photographs (black-and-white, colour, or infrared) and using photographs at different scales. The program calculates areas and locations through a link with a digital terrain model. There are numerous possible applications: calculating the percentage forest cover, identifying the edges of the forest, estimating the stability of mountain forest, and doing diachronic studies of forest dynamics.

Keywords: automated analysis of aerial photographs, automated assessment of forest cover, perception of forest dynamics, computer-assisted forest monitoring, software for forest analysis.

RÉSUMÉ

LE PROJET CLAPA: CLASSIFICATION AUTOMATISÉE DES FORÊTS À L'AIDE DE PHOTOGRAPHIES AÉRIENNES

Pour répondre aux besoins des experts-forestiers, un logiciel tournant sur PC de famille IBM ou Macintosh a été mis au point suivant une démarche généralement appliquée à la production en micro-ingénierie. Grâce au logiciel, il est possible de distinguer les arbres, les groupes d'arbres et les forêts denses sur des photographies aériennes numérisées de différents types (noir et blanc, couleur ou infrarouges) et prises à différentes échelles. Le programme calcule les superficies forestières et localise les forêts au moyen d'un lien créé avec un modèle numérique de terrain. Le logiciel a de nombreuses applications; il est notamment utilisé pour le calcul du pourcentage de la couverture forestière, la délimitation des forêts, l'évaluation de la stabilité des forêts alpestres et l'étude diachronique de la dynamique forestière.

CONTEXT

The Swiss Federal Institute for Forest, Snow and Landscape Research (FNP) is located in the German-speaking part of Switzerland, but in 1990 a small unit (Antenne romande; AR) was opened in the French-speaking part of Switzerland, at the Swiss Federal Institute of Technology, Lausanne (EPFL). This unit (AR-FNP) does research and makes information accessible to a wide audience concerning forest management, forest

ecology and the value of forest products. These activities are carried out together with FNP, and in collaboration with partners who have the necessary expertise and infrastructure at EPFL and in universities of the French-speaking part of Switzerland.

The AR-FNP is in close contact with forestry practitioners so it can identify their needs for research to be done and forward these to the scientists best suited to act as partners. The CLAPA project described here is a good example of this approach.

NEEDS OF FORESTRY PRACTITIONERS

At some time or other all Swiss foresters need to use aerial photographs for their work of planning, management and control. Aerial photographs are complementary to work on the ground and give information essential for making maps of populations, planning interventions, mapping, determining the limits of the forest, evaluating forest damage, estimating the percentage of forest cover in forested pastureland and so on. Each administrative unit in the forest has its own collection of aerial photographs, or else these can easily be obtained from the cantonal service.

The work of interpreting aerial photographs involves examination and assessment by an operator who manually transcribes the information onto a map, in particular if diachronic series of photographs are to be compared. With the increasing use of computers, data are more frequently digitized and managed through a geographical information system (GIS). However, the data are still produced through the long and arduous task of stereoscopy, which is tiring for the eyes, and above all costly.

Despite their lack of stereoscopic effect, orthophotos are often preferred because they give better precision and the different zones of interest are transferred in a direct, geometrically-valid manner. This process is particularly useful when the work is done directly from a GIS onto digitized images on the screen, linking to different layers (land register or other digitized maps) depending on particular needs. Although the cost of producing orthophotos has fallen significantly over the past few years, they are nevertheless expensive reference documents, usually requiring particular flights to be carried out. It is mainly for this reason that orthophotos are still only used to a very limited extent for forestry planning.

Thus the usefulness of aerial photographs is generally recognised, but their use is limited by the time and cost involved in processing them. We are told by foresters that they wish to make greater use of aerial photographs. They are keen to have a computing tool capable of extracting the information that they need in the most automatic way possible from aerial photographs which have already been digitized. This can be information on internal and external forest edges, natural or artificial clearings (trees blown down by the wind), percentage of forest cover, an indication of the species present (at least a distinction between conifers and broad-leaved species) and on natural regeneration. As far as possible these data need to be extracted on the spot, within the administrative unit of the forest, using the PC or Macintosh computers available.

DATA AVAILABLE

The procedure followed in the CLAPA project is similar to that in industrial production: once the needs of the clients have been clearly identified, they should be satisfied at the lowest possible cost, using existing, inexpensive components as far as possible. Logically, in the present case the data available need to be arranged in analogical and digital form, along with local particularities which are especially significant. The analysis following on from these initial conditions will indicate not only the directions which research should follow, but also how much room there is for manoeuvre.

Aerial photographs

For several decades the most readily-available aerial photographs in Switzerland have been the black-and-white photographs of the Federal Office of Topography (OFT). The first complete survey of the country by OFT photographs suitable for stereoscopic interpretation dates from the early 1950s (scale of about 1:25,000). Since then a sixth of the area of the country has been photographed every year. These aerial photographs are taken mainly for updating the national maps, and they are the most recent and richest source of information in

space and time which is available. They are now taken at a scale of about 1:33,000, and under optimal conditions give a resolution of about 25 cm at ground level. These black-and-white photographs are mostly taken with a 153 mm lens and are in the spectral range of 400 to 700 nm. Each one has a format of 23 cm X 23 cm and covers an area of 55 to 60 km².

These aerial photographs are of excellent quality and readily available, but they are particularly useful because they are taken periodically, which enables forest changes and the dynamics of the landscape to be analysed in space and time for any part of the country. There is also information from other kinds of aerial photographs taken in response to particular needs, and dating back to the 1920s.

Nearly 47,000 infrared aerial photographs at scales of 1:9,000 and 1:3,000 were taken between 1984 and 1991 during the national Sanasilva programme on forest damage (Wandeler *et al.*, 1992). They cover more than half the area of Swiss forests. In addition, several cantonal forest services have done total or partial aerial surveys of their forest areas.

To facilitate the use of aerial photographs of all types, the Federal Directorate of Cadastral Surveying annually publishes a catalogue of photogrammetric flights carried out in Switzerland and financed by the Swiss government. Managing these photographs, including making them available for loan, is greatly facilitated by the development of a GIS for this purpose. At present there are more than 100,000 photographs, not counting those of the OFT (Gautschi and Hägeli, 1997).

Digital terrain model (DTM)

In Switzerland there is fortunately a digital terrain model, the "DHM25" (Digitales Höhen Modell) of the OFT, with a point every 25 m. This has been obtained by interpolation of the contour lines on the 1:25,000 national map (10 m between contour lines). In many parts of Switzerland where there is a sudden change in slope, specific measurements are done to improve the reliability of the data. The precision of the model varies depending on the zone considered: on the plateau the RMS (root mean square error) is of the order of 2 to 4 m, but it can be up to a few tens of metres in rocky areas in the Alps.

Particularities of forest ownership in Switzerland

Switzerland has a population of about 7 million people and an area of less than 42,000 km². This is made up of 38% agricultural land, 22% rocks and glaciers, 4% lakes and rivers, 6% towns and cities and 30% forest, which means about 1.2 million hectares of forest (OFEFP, 1995). About 73% of Swiss woodland is publicly owned (by communes, cantons, and the Swiss government). The average area of privately-owned forests (250,000 owners) is only 1.2 ha, whereas public forestry enterprises average 310 ha.

The Swiss forest is protected by a comprehensive forestry law. This is the result of long tradition, with the first forest legislation dating from 1876. The forestry law states the principles of conservation in terms of area covered and geographical distribution and the protection of the forest as a natural area. It also ensures that the many functions of the forest are maintained (for instance, clear-cutting is forbidden). The area of forest is divided into beats (areas of about a hundred to a thousand hectares) and into districts (areas of about a thousand to twenty thousand hectares), and these are managed and controlled by competent, trained technical personnel and forestry engineers.

There are certain particularities of Swiss forest ownership, with small areas managed by a silviculture attuned to nature. Innumerable landmarks and a very high density of boundary marks and official measurement points noted in the land register (which is being digitized) facilitate all types of reference to points.

Conditions imposed on the tool to be developed

The needs of forestry practitioners, the basic data available, and the context described above all influenced the first list of requirements for developing software for the automated classification of digitized aerial photos (Table 1), known as CLAPA.

Software	Data	Results
• PC or Macintosh platform • Simple to use, user-friendly • Short processing time • Interactive, with individual settings, selected from simple, basic settings	• Black-and-white photographs, and other types too • Photographs to be digitized using a readily-available scanner • Link with a DTM without going through the creation of orthophotos	• Identification and geocoding of forest limits (internal and external forest edges), and of single trees, groups of trees, also area measurements • Table of data • Processed image • Usual export formats, including towards GIS

Table 1. Basic conditions imposed on the tool to be developed.

It is worth stressing certain aspects which influence the approach chosen, in particular the accessibility of the software using computing resources available at the level of the district and the beat. This means the software has to be developed to run on a PC or Macintosh computer, needs to be simple to use, and user-friendly in a similar way to the most usual current software. Acquiring data is strongly influenced by the fact that only files of a "reasonable" size can be easily dealt with and processed. It should preferably be possible to digitize photographs using reasonably-priced scanners.

Concerning the basic settings before the photograph is processed by the software, there should be a logical sequence, in an interactive framework. It needs to be possible to export the results of the processing by the software towards word processors, spreadsheets and GIS.

The level of precision required of the software needs to be adapted depending on the particular needs of the users. The software is intended mainly for forestry and landscape professionals, not for surveyors or urban planners, so it can be allowed to gain in working time what it loses in precision, as long as it gives an indication of the level of precision. For instance, the detection of gaps as a zone where avalanches may start in a forest whose primary function is protection requires a higher level of precision than determining the percentage of forest cover in forested pastureland. In the latter case the level of the area (100 m²) is considered as extremely precise, or even excessive, and even the level of the hectare is considered as very precise. This is not the case when the stability of mountain forest has to be considered, because an avalanche can start in natural or artificial spaces which are more than 30 m along the line of the slope and more than 50 m (or two lengths of a tree) along a contour line (Meyer-Grass, 1985).

CLAPA: AN IDEA WHICH IS PROGRESSING

The pilot project "CLAPA: Classification Automatisée de Photos Aériennes (automated classification of aerial photographs)" was launched by AR-FNP in 1993 (Bodmer, 1993), and lasted four months. Through a detailed study of the literature it was shown that there was surprisingly little reference work directly in relation with the subject and no software allowing the automatic analysis of aerial photographs in the way mentioned above. As far as we know this is still the case today. Serious indicators were noted for the analysis of texture and the recognition of objects.

There was no doubt of the necessity to link the software with a GIS and to use a DTM if one wished to produce a geocoded classification. However, this did not mean that a working classification tool would be developed for the forestry practitioner. It was also difficult to imagine that the tool developed would be able to function with the computing means available to the forestry services, run by foresters themselves.

MICROENGINEERING APPROACH

During a seminar on the recognition of objects organised by the Department of Microengineering of the Swiss Federal Institute of Technology (EPFL), contacts with its Institute for Microengineering Production (IPM) (at that time known as IMT) revealed common interests in resolving the problem sketched out by the CLAPA pilot project. The extraction of elements of images, referring to a schematic model is part of the activities of IPM in the field of vision. In fact a group at IPM is working on locating position based on a model.

The image of the object whose position is to be located has to be compared with the symbolic model which has previously been memorised. It is first necessary to establish correspondence between the object and its model, then faults in the object compared with the ideal model are identified. This approach then replaces the image of the object by a virtual image of the model and removes the adverse effects of the faults in shape of the real object in the calculation to find the position. In addition, this allows one to do all the calculations on a model which only contains useful information without carrying through an enormous amount of information linked to the images.

The first practical approach was an undergraduate semester study (Kreiss, 1995). In view of the promising results this research was continued in a diploma study lasting four months (Kreiss, 1996) resulting in a prototype software. Then two months of improvements and fine-tuning made the software operational and enabled some fields of application to be explored (Barbezat *et al.*, 1996). The software was named CLAPA, to indicate continuity with the pilot project.

NEED FOR A GIS

This work at IPM was accompanied by interactive thinking between foresters and researchers, taking into account the practical aspect. The definition of steps in the work (Figure 1) has shown the fundamental aspect of linking to a GIS, which has become an essential tool in forestry. The expertise of AR in this field, greatly supported by specialists in the Department of Rural Engineering (Institute of Photogrammetry; Chair of SIRS), were exploited in the different tests. Optimal functioning of CLAPA can only be achieved together with external GIS and databases.

PRINCIPLE OF OPERATION OF CLAPA

Before the software is used a certain number of preliminary tasks are essential. This requires a scanner and software for processing images (such as Adobe Photoshop™).

Digitization of the photograph

The photographic image has to be digitized at a resolution such that one pixel corresponds to about a 80 cm-sided square on the ground. This resolution, which depends on the scale (in Switzerland the smallest scale is 1:35,000), can be achieved with good flat-bed scanners (1,200 to 2,400 dpi), which are at present sold for less than 2,000 Sfr. Higher resolution does not significantly improve the precision of the results, except perhaps for regions with high rates of natural regeneration by individual trees less than one metre high. Normally the software only takes into account trees over 1 m in height (parameterizable limit).

Work on the image and introduction of basic data

The image is rotated so that the axis of the shadows is oriented vertically. This saves software working time.

The program also requires the operator to supply the following information:

- coordinates of the corners of the image as used in the Swiss national geographical coordinate system,
- date and time when the photograph was taken,
- altitude from which the photograph was taken,
- focal length of the lens used to take the photograph, and scale of the photograph.

Linking to a DTM

The CLAPA system works on the basis of aerial photographs taken from an aeroplane flying at an altitude stabilised as a function of the altitude of the local terrain, to ensure that the resolution of the photographs is always similar. In steeply sloping areas, which are common in Switzerland, this height above the ground

inevitably varies. The central projection made by the camera to obtain the photograph on a plane implies a difference in the sizes of real objects depending on their distance from the aeroplane.

Cartographers solve this problem very effectively by creating orthophotos. This type of correction requires substantial computing resources, and a considerable amount of time to identify the stereoscopic images, and to do the calculations.

CLAPA seeks to achieve a precision in measuring forest areas of the order of 2 to 3% of the total area, without using complicated computing equipment. It is possible to manage without stereophotography as long as the data for the altitude at which the photograph was taken (which are on the photograph) and the DTM of the OFT are taken into account. These data allow the enlargement of each point on the photograph to be calculated. This is not necessary for the precision mentioned above, and a procedure by close zones of altitude is enough.

The coordinates of the rectangular surface circumscribing that of the image to be processed make it possible to extract the DTM of the zone of interest using a small routine. The two extreme altitudes of the whole image are then identified. From these points horizontal slices are constructed of a thickness depending on the altitude from which the photograph was taken. Each level is thus given a coefficient depending on its altitude and, therefore, its distance from the aeroplane, measured perpendicular to the plane passing through the aeroplane. Of course this correction is superimposed on the one which depends on the horizontal distance to the normal passing through the point of observation.

From a practical point of view this method gives very good results within the range of precision which interests us, even for zones of forest on steep slopes. In addition, this approach is very rapid in terms of calculation time and does not require large memory capacity.

Processing the digitized image

Referring to the grey scale of the grassland single trees are identified by the presence of their shadows. The shape and the area of their shadows allow objects to be distinguished on the image, just keeping single conifers (Figure 2 and 3). Various types of processing allow the diameter of the crown to be defined, so that the orthogonal projection can be deduced. Depending on the date and time that the photograph was taken, and the DTM, it is possible for the software to calculate the height of a tree from the length of its shadow. Another way is to use a linear approximation from a forestry database, giving average dendrometric values for the region where the photograph was taken, in this case the relation between crown diameter and height.

For groups of trees and dense forest, the shadow is not used in the same way; the image is processed in a fairly conventional way using a gradient filter, followed by thresholding, a low pass filter, expansion, filling-in of holes, and finally erosion.

Figure 4 corresponds to the image resulting from basic processing. The interpretation which the system then does is based on modelling conifers, in the present case spruce (*Picea abies*), integrated in the processing software. The data necessary for this modelling also come from the dendrometric database (Lässig et al., 1992). The maximum dimensions and the range within which the ratio between height and crown diameter varies are therefore known. This allows trees to be identified and deductions to be made on the likely number of individuals in a group. Figures 5 and 6 show how groups of trees have been represented for a larger portion of image. A group of trees means here at least two trees with their shadows touching. Processing the image in this binary form is extremely rapid as the file is very small.

The system sometimes locates two trees instead of three, but it is found that the assessment of the size of the forested area is still a good approximation.

Even from precise measurements on the ground, calculating the orthogonal projection of the crown of a tree is still an approximation which depends on the method used.

CASE STUDIES

Once the existence of the software had been made known to the public, numerous requests for it to be applied came from forestry practitioners. Test sites were chosen in the proposed zones of forested pastureland. These have many particularities, some of which were very useful for us. Forested pastureland falls within the scope of the Federal Law on Forests, and in a small area of forested pastureland there will be a mosaic of different forest landscapes, from single trees to dense forest. Except for the slope, forested pastureland bears a strange resemblance to zones at the timber line (Bodmer and Barbezat, 1994). A very thorough study, called PATUBOIS (Gallandat et al., 1995), showed that the percentage of forest cover is a basic element, which is essential for doing a dynamic model of forested pastureland.

Initially the question of the relief of the terrain was not considered in CLAPA; it is only recently that a DTM has been linked to the software. The almost flat zones of the Breuleux region (Franches-Montagnes, Jura) were very useful, since the work was able to concentrate on forest identification by the software.

Complete study

Tests of the software were mainly carried out on areas of ten to twenty hectares, under forest conditions which differed geographically and geomorphologically.

A large test was done on an area of 400 ha: the forested pastureland of Communal de la Sagne, in the canton of Neuchâtel. This pastureland comprises twenty forest divisions (of a few hectares each) for which a new management plan has to be defined by the forest engineer in charge (the first management work was done in 1894, with revisions about every ten years since then). This work requires an estimation of the percentage of forest cover. It should be remembered that this is a key element in several ways for forested pastureland: it influences the quality of grazing land (Troxler, 1992) for agriculture, and the quality of timber, but above all it affects the quality of the landscape and biodiversity, which are to be managed by the forester.

The twenty divisions were analysed individually by CLAPA. A few seconds of processing time were needed per division to calculate the total area, the forested area, percentage of forest cover, and the locations of single trees with their heights. For certain divisions the possibility of setting the software interactively was used. This resulted in considerable differences in the detail of the interpretation of the forest mosaic (Figure 7). For the forest practitioner this corresponds perfectly to the initial choices which need to be fixed clearly; for instance, does one wish to have detailed information on natural regeneration and its dynamics, or is one only interested in large areas of forest which are more or less dense? This also raises the question of the objective definition of the notion of forest, which is different for matters of forestry policy and supervision as opposed to ecosystem management.

PROSPECTS

The results obtained encourage us to continue beyond the semester study and diploma work. A doctoral project would amongst other things permit the exploratory work and the solutions found so far to be re-examined in a critical way.

The CLAPA software was developed using other software, Labview™ with Concept V. i™. For this reason certain steps in the processing are still less transparent than desired. It is intended that the software will be completely rewritten, as modules, in a traditional programming language.

Certain problems, both internal and external to the software, still have to be resolved, for instance:

- Precision and reliability of the results, in particular to increase its usefulness for mountain forests.
- Geocoding the image by points in the image, not by the coordinates of the corners.
- Reduction in the sizes of the files by compression or the use of other formats.

- Influence of characteristics specific to each image, including the dynamics of slides from OFT, with a view to their use in forestry (forest less dark, and more subtle).
- With an *ad hoc* module, possibility of projecting maps at any scale onto the photograph, using the centre of projection. Conversely, it should be possible to measure the distances and coordinates of all points on the photograph, with an indication of the level of precision.
- Influence of the type of scanner used for digitizing the photograph.
- Definition of the type of forest, and the forest - non forest limit.
- Interactions with GIS need to be further improved, taking into account the use of GIS in the forest management unit, and the databases which are linked to it.

The last point raises the question of external databases relating to the morphological characteristics of forest species, which are necessary for the object recognition part of the software. In fact the power of CLAPA depends on the relevance of the information contained in these databases. Differentiating between conifers and broad-leaved trees is a priority. Ecological characteristics linked to altitude, exposure and the distribution of species will enable powerful exclusion criteria to be formulated, with a reduction in processing time for the software. Linking to statistical databases such as GEOSTAT (OFS, 1985) could also be very useful.

The CLAPA software is of course mainly for use in the forest, and it is intended for forest managers. However, the usefulness of CLAPA in other sectors of landscape should also be tested and perhaps developed. The software is excellent for collecting and compiling information contained in a diffuse form in an image. This is useful for the objective quantification of changes in certain parameters of ground cover, as can be observed from diachronic series of aerial photos. This should enable its use to be considerably extended, for instance in relation to the sustainable management of ecosystems.

For the CLAPA project to be really successful, and for it to develop under the best possible conditions, the involvement of specialists in different fields is essential. This is one of the many interesting aspects of the project. Through the present communication we hope to attract the interest of various researchers and potential users, leading, we hope, to all sorts of collaborations and synergistic interactions between people working in different fields.

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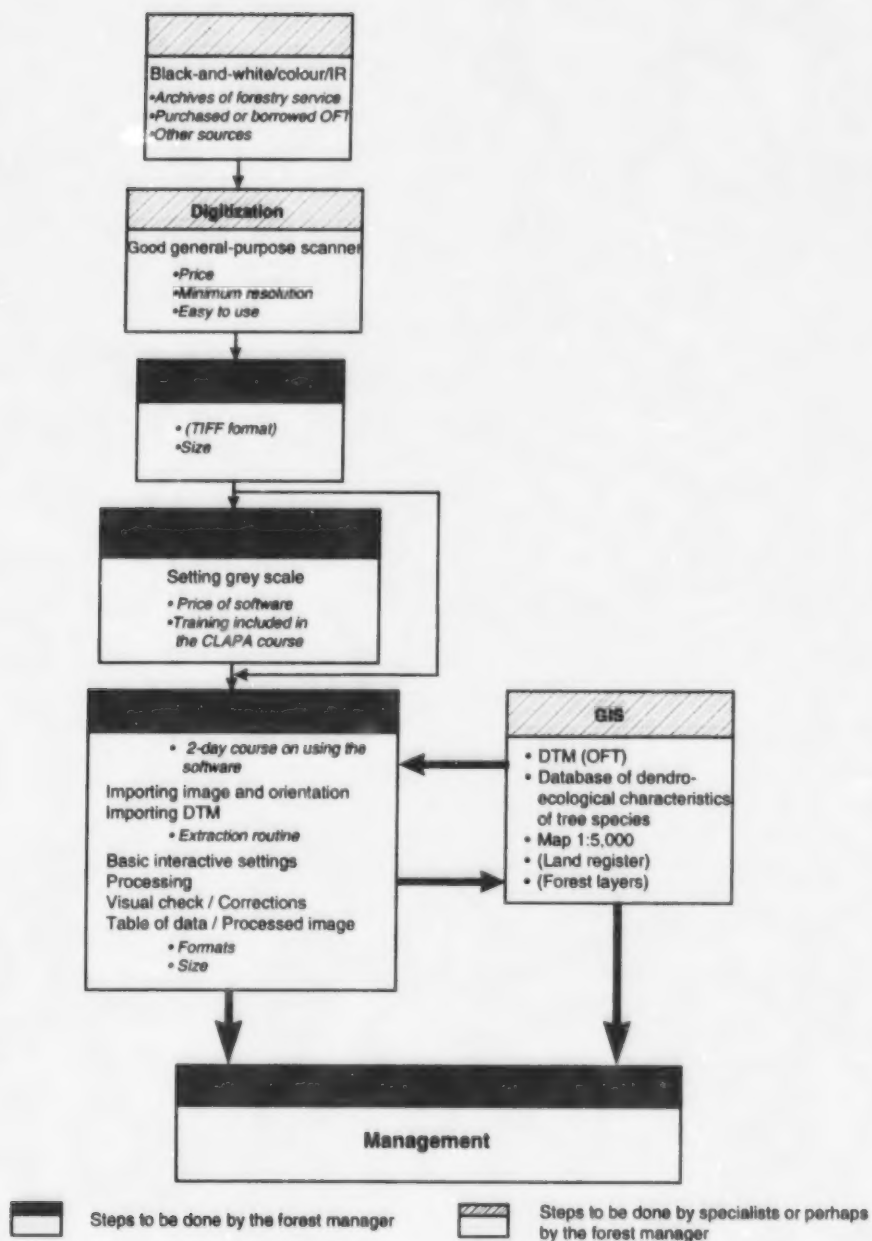


Figure 1. Steps and conditions for automated classification used in the CLAPA project.

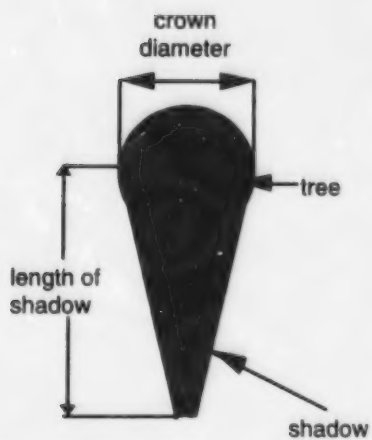


Figure 2. Schematic representation of a single spruce tree with its shadow (Bodmer, 1993).



Figure 3. Result from the program.



Figure 4. Extract of image after basic processing.

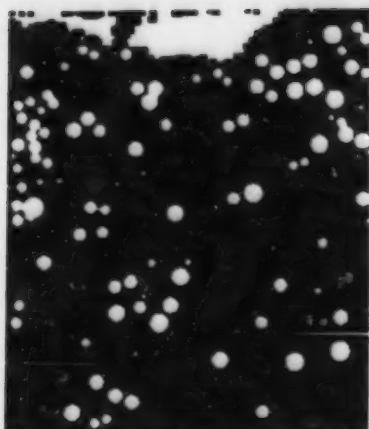


Figure 5. Binary image of the zone enlarged: the orthogonal projection model replaces the particles.



Figure 6. Binary image superimposed on the original image.



Figure 7. Effect of software settings on processing detail, example with the same portion of image.

PHOTO ECOMETRICS FOR FOREST INVENTORY

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ABSTRACT

In this paper, we report the results obtained from the application of digital photogrammetry and hyperspectral data analysis for forest inventory purposes. Our long term goal is to provide low-cost yet accurate estimates of as many important forest biophysical parameters as can be measured and inferred with airborne digital cameras. Accuracies of traditional multispectral image analysis algorithms of remotely sensed data are low. Traditional photo interpretation is error prone and expensive. We propose new image analysis strategies that make use of the 3D spatial morphological information from stereo images and the multispectral, texture and contextual information inherent in the imagery.

Research on the use of 3D crown shape information in automated tree species recognition has not been reported before. The minimum requirements of image spatial resolution for deriving estimates of tree heights and crown size with high accuracies are not known. With digital photogrammetry, it has been proven that digital camera images can be georeferenced and orthorectified to an accuracy of one to several meters allowing for selecting ground control points directly from digital camera images for georectification of other images including high resolution satellite images. With the georeferenced and orthorectified digital camera images and the above parameters accurately determined, we can detect changes of species composition, height, crown closure, and diameter. These same techniques will significantly improve our ability to economically assess the accuracy of thematic vegetation maps.

Keywords: tree species, crown closure, size, digital photogrammetry, hyperspectral analysis.

RÉSUMÉ

PHOTOÉCOMÉTRIE APPLIQUÉE À L'INVENTAIRE FORESTIER

Ce rapport fait état des résultats de l'application de la photogrammétrie numérique et de l'analyse de données hyperspectrales à l'inventaire forestier. Notre objectif à long terme consiste à évaluer avec précision et à peu de frais autant de paramètres biophysiques forestiers qu'il sera possible d'extraire et de mesurer à partir d'images captées par caméras numériques aéroportées. Les algorithmes classiques d'analyse d'images multispectrales obtenues à partir de données de télédétection donnent des résultats peu précis, tandis que la méthode traditionnelle de photo-interprétation est coûteuse et souvent source d'erreurs. Nous proposons donc de nouvelles stratégies d'analyse d'images qui reposent sur l'information spatiale tridimensionnelle obtenue sur la

morphologie à partir d'images stéréoscopiques ainsi que sur l'information multispectrale, texturale et contextuelle tirée de cette imagerie.

Aucun rapport de recherche sur l'utilisation de l'information tridimensionnelle sur la forme des houppiers aux fins de la reconnaissance automatisée des essences forestières n'avait encore été établi. Les exigences minimales quant à la résolution spatiale requise pour évaluer avec un haut degré de précision la hauteur des arbres et la dimension des houppiers ne sont pas encore connues. Grâce à la photogrammétrie numérique, il a été démontré que les images captées par caméras numériques peuvent être géoréférencées et orthocorrigées avec une précision de un à quelques mètres, ce qui permet de choisir, directement sur ces images, des points d'appui au sol aux fins de la correction géométrique d'autres types d'images, notamment d'images satellites à haute résolution. En géoréférençant et en orthocorrigant les images fournies par caméras numériques et en définissant avec précision les paramètres susmentionnés, il est possible de détecter les changements dans la composition des espèces et de déterminer la hauteur et le diamètre des arbres ainsi que la fermeture du couvert. Ces techniques nous permettront également de mieux évaluer, d'un point de vue économique, les cartes thématiques de végétation.

INTRODUCTION

The need for detailed forest parameters (species, size, canopy density and numbers of trees) and other biophysical information over large land holdings in the United States has increased markedly in the last five years driven in large part by the information demand for modeling forest ecosystems, identifying forest habitat locations where threatened or endangered species such as the spotted owl or marbled murrelet may occur, and by regulations requiring sustainable forest management, particularly in the west. To efficiently manage forest landscapes for forest, wildlife, and other biological resources we need to have detailed information on forest composition and structure, but it is usually economically infeasible to collect the requisite 5-10% field sample. Thus, it is critically important to be able to develop new advanced remote sensing technologies that allow for direct measurement of the parameters needed for forest management and monitoring and substantially reduce the cost of obtaining this information compared to field sampling.

We propose an interdisciplinary field, ecometrics, the science and technology of obtaining reliable ecological measurements over large landscapes. Biologists have largely overlooked the field of ecometrics because it requires skills usually outside their expertise: remote sensing, photogrammetry, statistics, and biometrics. Nonetheless, development of this field is critical to provide the tools to aquatic and wildlife biologists, ecologists, foresters, and geographers to be able to measure and monitor landscape level ecosystem processes and land use changes.

This research falls in a subfield of ecometrics, photo ecometrics -- the use of photogrammetry and image analysis techniques to derive ecological parameters. Figure 1 outlines the possible components of photo-ecometrics. The focus of this research is the development of methods for forest information extraction from high-resolution digital aerial photographs to measure important forest parameters.

Use of airphoto interpretation techniques for forest species classification and crown closure estimation is dependent on the experience of photo interpreters. Some experiments indicate that there are large discrepancies among airphoto interpretation results carried out by different interpreters (e.g., Biging et al., 1991; Davis et al., 1995; Gong and Chen, 1992). On the other hand, it is difficult to accurately make detailed vegetation maps at the stand level with existing satellite imagery such as SPOT HRV and Landsat TM data because of their low spatial resolution ranging from 10-30 m (Brockhaus and Khorram, 1992; Franklin, 1994).

The current situation is that stereo photography lacks spectral depth, but allows for precise photogrammetric measurements. The current generation of satellite images have more and narrower spectral bands than photographs, but are not of high spatial resolution and high geometric precision. Digital cameras bridge this gulf by providing imagery which is of both high spatial and spectral resolution with a sufficient number of spectral bands. This will enable us to develop new computational algorithms for image processing

and softcopy photogrammetry to extract the maximum amount of information contained in remotely sensed images and to provide the parameters needed for forest management, monitoring and ecological studies.

DIGITAL PHOTOGRAMMETRY FOR FOREST MEASUREMENT AND CHANGE MONITORING

Digital photogrammetry is a computerized technique that automates the measurement and mapping process of traditional photogrammetry. It includes all the procedures of traditional photogrammetry such as photo orientation, stereo model construction, aerial triangulation, contour and orthophoto generation, photo mosaicking and mapping (Saleh and Scarpace, 1994). A major challenge in digital photogrammetry is image matching, a critical procedure that finds image points from the left and right photographs that correspond to the same ground points. Although many algorithms of image matching have been suggested (Ackermann, 1996), this process is error-prone in forest and urban areas where abrupt vertical changes are common. The two primary uses of digital photogrammetry are digital elevation model (DEM) development and orthophoto generation. A DEM of an area is usually an array of grid points of ground elevation that exclude the heights of landscape features such as forest and buildings. For the purpose of forest measurement, a digital surface model (DSM), an array of grid points of elevation of landscape features, is necessary. An orthophoto is a photo of an area that has a constant scale and is free from point displacement caused by elevational differences. Therefore, area measurements from orthophotos are more accurate than from raw aerial photographs.

Figure 2 shows the results from digital photogrammetry when applied to two sets of scanned aerial photographs acquired in July 1970 and August 1995. The original photos were acquired with a nominal scale of 1:12,000 at the upper Gallinas Valley, Marine County, California. They were scanned at 1000 DPI from black and white diapositives on a Vexel 3000 scanner. The digital photogrammetric software used to analyze these photos were SocetSet and VirtuoZo. Results shown here are generated automatically from digital photogrammetry. Because we did not collect ground control points, all photos were relatively orientated by assuming one of the photographs in 1970 as vertical with a scale of 1:12,000. Figures 2a, 2b show the 1970 and 1995 orthophotos for the same area, respectively. Figures 2c and 2d are the 1970 and 1995 DSMs, respectively. Figures 2a and 2b were generated by projecting the raw photo onto the 1970 and 1995 DSMs, respectively.

The scanned image resolution was approximately 30 cm. The grid spacing used to extract the DSM was approximately 1 m. The DSM shown in Figures 2c and 2d were interpolated to 30 cm. The surface cover is mainly hardwood rangeland. Clusters of relatively bright areas, in Figures 2c and 2d, are coastal live oaks. Coastal live oaks can be extracted from Figures 2a and 2b through a simple image thresholding as they are much darker than their surroundings. Changes of crown closure can be obtained by comparing the two thresholded images. Changes in tree heights can be obtained by subtracting the 1970 DSM from the 1995 DSM.

Figure 3 compares crown closure derived from the raw imagery and the orthophoto at a slightly different location. Crown boundaries are both obtained from image grey level thresholding. The boundary displacement caused by surface elevation on the raw image is obvious in an area where the elevational change is less than 60 m. The crown closure measured from the raw imagery represent a 9.9% overestimate of the actual crown closure as approximated by that measured from the orthophoto.

The lessons we learned from experiments with aerial photographs will be used to develop algorithms for analysis of images acquired from digital aerial photography. We have integrated fully digital system with a digital camera, GPS and inertial navigation systems. A preliminary test of the system was carried out with digital photography taken over the Berkeley campus in January 1997. When the system using a 28 mm camera lens is flown at 1000 m above the ground, a georeference accuracy of 2 m in the horizontal, 3.6 m in the vertical direction can be achieved (Mostafa et al., 1997). This implies that the system can locate points on the ground with 2-3 m accuracy with no need of any ground control points in the area of interest.

TREE SPECIES RECOGNITION

Tree species recognition is difficult in traditional remote sensing image analysis. With experience gained in the application of neural networks from some previous studies (e.g., Gong, 1996; Gong et al., 1996), we evaluated its potential in classifying 6 conifer species based on hyperspectral data collected using an Ocean Optic® portable hyperspectral radiometer. The 6 conifer species are typical in the Sierra Nevada mountains in California. Our measurements were collected in the field from 4-7 year old trees at the Blodgett Forest Research Station operated by the Department of Environmental Science, Policy, and Management at the University of California at Berkeley. With approximately 4500 acres of conifer forest land, this site is located in the American River watershed on the western slope of the Sierra Nevada in El Dorado County of California. Main conifer species of northern California include giant sequoia, Douglas-fir, white fir, ponderosa pine, sugar pine and incense cedar, of various ages.

Our recent analysis of hyperspectral measurements taken from six conifer species at the Blodgett Forest has produced excellent results in tree species separation. With spectral derivative applied to the hyperspectral measurements and the use of a feed-forward back-propagation neural network algorithm we consistently obtained better than 80% accuracies of discriminations of the six conifer species at several sites in either summer or late fall seasons (Gong et al., 1997). Discrimination accuracies for the six species at some sites exceeded 90%. These results are helpful to our band selection effort.

In a recent study, we applied six types of transformation to the hyperspectral reflectance data (R), preprocessed with a simple smoothing, followed by band merging. These include $\text{LOG}(R)$, first derivative of R , first derivative of $\text{LOG}(R)$, normalized R ($N(R)$), first derivative of $N(R)$, and $\text{LOG}(N(R))$.

Table 1 lists overall accuracies in percentage obtained from classifying each of the 12 sets of data (2 sides of canopy X 2 sites X 3 seasons) by neural networks. The neural network structure and parameter settings are approximately the same as those presented in Gong et al. (1997). The averages of overall accuracies for the sun-lit and shade sides of canopies have been listed at the right end of the table. The average overall accuracies exceed 90% for data collected from both the sun-lit and shade sides of canopies. The average of sunlit and shade accuracies is 91.3%. The best transformation method seems to be the one taking the derivative after taking the logarithm. This is closely followed by the method of taking the derivative after normalization, which yielded an average of all accuracies of 90.1% and taking the derivative alone, which yields an average of all accuracies of 85.3%. The three top ranked transformation methods produce average accuracy improvements of 23%, 21.8% and 17%, respectively, over the 68.3%, the average of all accuracies obtained from the original data without transformation. Taking the logarithm alone resulted in a decrease of 3.9% in average of all accuracies. Conducting the normalization alone or taking the logarithm after normalization resulted in small accuracy improvements.

Comparing the accuracies obtained from derivative spectra with corresponding non-derivative spectra ($D(R)$ vs. R , $D(\text{LOG}(R))$ vs. $\text{LOG}(R)$, and $D(N(R))$ vs. $N(R)$), we can see that taking the derivative has greatly improved classification accuracies. Most of the accuracy improvements are between 15-30%, while some are greater than 36%. In one instance a decrease of 0.7% was obtained between $D(R)$ and R for the measurements collected from the shade sides at the Fenced site in June 1996.

From the above analysis, it can also be seen that the effect of hyperspectral data taken from the shade sides of tree canopies can be minimized by applying normalization or by taking the derivatives after applying a logarithm to the preprocessed data. A big difference in solar angle did not cause a noticeable difference in accuracies of species recognition.

Transform	G site 10/95		F site 10/95		G site 6/96		F site 6/96		G site 11/96		F site 11/96		Average		
Types	Sunlit	Shade	Sunlit	Shade	Sunlit	Shade	Sunlit	Shade	Sunlit	Shade	Sunlit	Shade	Sunlit	Shade	Overall
R	70.8	59.2	58.3	35.0	75.8	65.3	81.9	90.3	74.2	60.8	75.0	73.3	72.7	64.0	68.3
D(R)	85.0	95.8	65.0	45.0	90.8	81.7	93.1	89.6	95.8	97.6	94.2	90.0	87.3	83.3	85.3
LOG(R)	60.8	55.8	50.8	41.7	78.3	60.0	77.8	89.6	60.1	65.7	60.8	70.8	64.8	63.9	64.4
N(R)	65.8	64.2	51.7	42.5	72.5	66.7	84.0	91.7	79.8	78.4	76.7	80.8	71.8	70.7	71.2
D(LOG(R))	91.7	94.2	79.2	64.2	93.3	92.5	97.2	97.9	96.6	99.2	93.3	96.7	91.9	90.8	91.3
LOG(N(R))	63.3	60.0	48.3	43.3	71.7	65.0	85.4	93.8	76.5	71.8	75.0	79.2	70.0	68.8	69.4
D(N(R))	93.3	93.3	80.8	56.7	91.7	85.0	95.1	95.1	98.3	97.6	97.5	96.7	92.8	87.4	90.1

Table 1. Percent species recognition accuracies using spectral reflectance measurements collected from sun-lit and shade canopies of individual trees at 2 sites and 3 time periods at the Blodgett Forest.

CONCLUSIONS

Digital photogrammetry has the advantage of supplying 3D information from stereo aerial photographs for subsequent analysis. We demonstrated that this information is useful in estimating tree heights, removing feature displacement in the image and thus leading to more accurate crown closure estimation. We will further test its potential in distinguishing shaded tree canopies from background shadows and the use of tree canopy shapes in species recognition. Our analysis of *in situ* hyperspectral measurements has indicated that the six conifer species can be discriminated with neural networks at an accuracy of greater than 90%. Taking the derivative of the hyperspectral data, or taking the derivative after the logarithm or after the normalization of the hyperspectral data promise satisfactory species recognition results. These transformation methods are not sensitive to solar elevation changes. Further research will be directed to optimal band selection and applying the optimal spectral bands to digital photography. The combined strength of high spatial resolution digital aerial photography and high spectral resolution optimal band setting will be evaluated in the context of forest species recognition and measurements.

ACKNOWLEDGEMENTS

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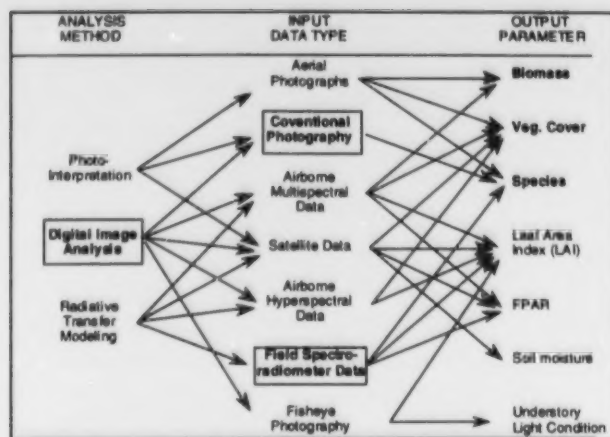


Figure 1. Possible components of photo ecometrics.

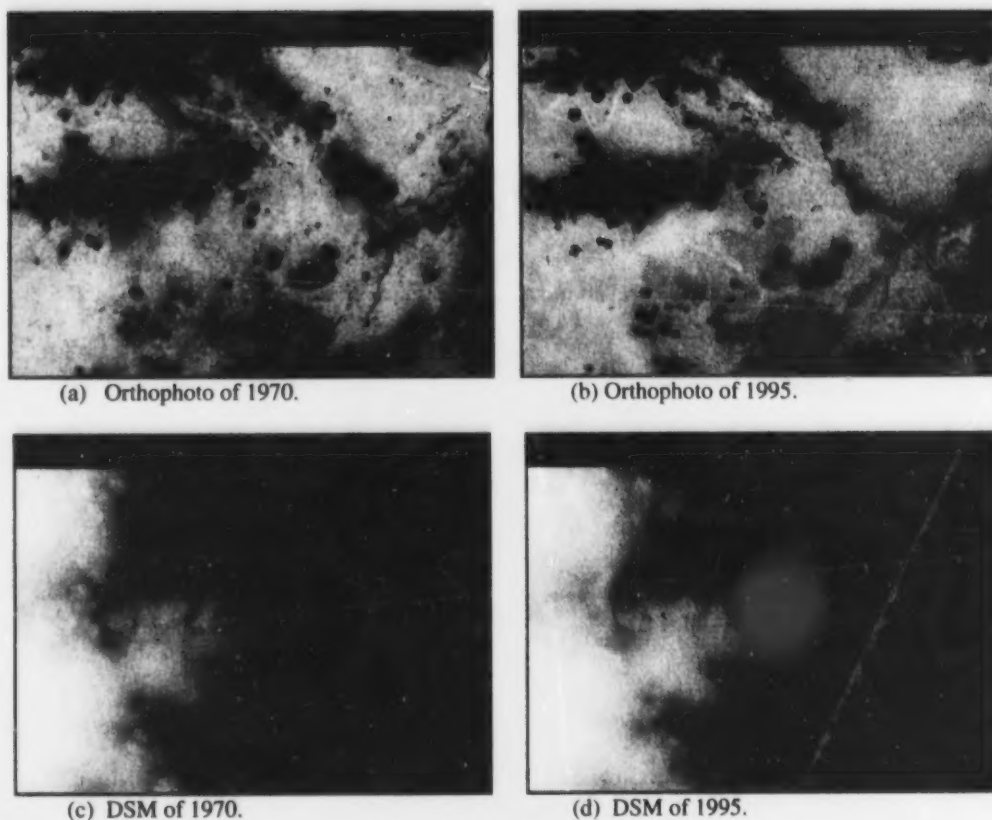


Figure 2. DSMs and orthophotos of a hardwood rangeland area. Greyscales in c and d are surface elevations.

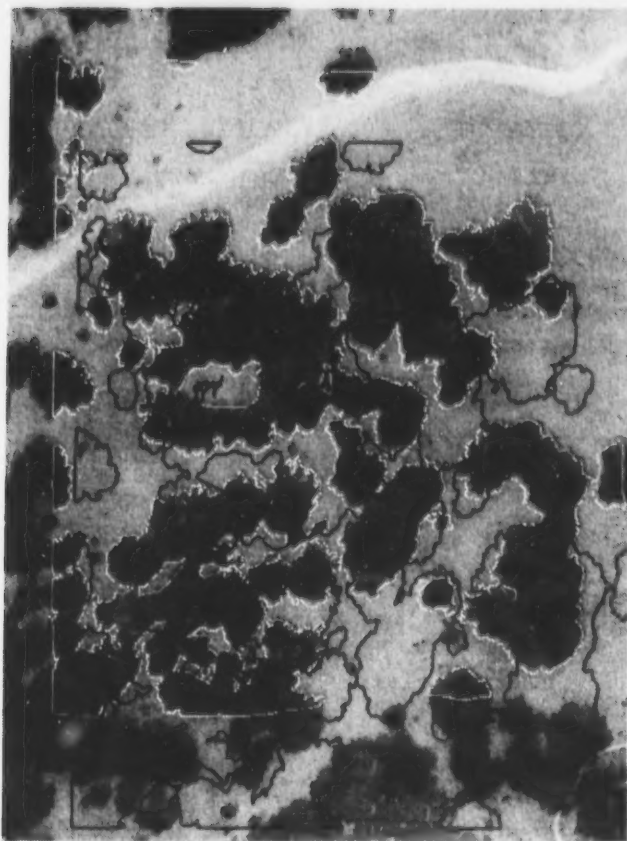


Figure 3. Crown closure boundaries extracted by image thresholding. White lines were derived from the orthophoto, while the black lines were obtained from the raw imagery.

Other Applications

REMOTE SENSING AND CRITERIA AND INDICATORS OF SUSTAINABLE FOREST MANAGEMENT

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ABSTRACT

The issue and concept of sustainable development have been popularized globally by the Brundtland Commission's report, "Our Common Future." Sustainable development is defined as "economic development that meets the needs of the present generation without compromising the ability of the future generations to meet their own needs". The concept was developed for biological systems; forestry and agriculture particularly. Since the tabling of the Brundtland report, sustainable development has captured the imagination of the public as well as of policymakers at local, national and international levels. This is a desirable objective for all individuals, institutions, economic sectors, societies and indeed for the global community at large. The term has stimulated much world wide discussion at the conceptual level, but little elaboration on how to apply it.

The increasing commitment to environmental stewardship also reflects the view that the environment, including its natural resources, is not an asset inherited from the past but one held in trust for the future. Consequently, forest practices must maintain the productive and renewal capacities of forest ecosystems for future generations. Non-timber forest values such as aesthetics, wildlife and fisheries habitats, and watersheds must also be protected.

Policymaking communities are faced with the need to reconcile national interests with international responsibilities and to develop flexible policy instruments, and institutions. Sustainable forest development means recognizing the limits of forests to withstand environmental change, and managing human activities to produce the maximum level of benefits obtainable within these limits.

RÉSUMÉ

LA TÉLÉDÉTECTION ET LES CRITÈRES ET INDICATEURS DE L'AMÉNAGEMENT DURABLE DES FORÊTS

Le thème et le concept du développement durable ont été popularisés à l'échelle mondiale par le rapport de la Commission Brundtland intitulé *Notre avenir à tous*. Ce dernier définit le développement durable comme « un développement économique qui répond aux besoins du présent sans compromettre la possibilité pour les générations futures de satisfaire les leurs ». Ce concept a été défini en fonction des systèmes biologiques, notamment des forêts et de l'agriculture. Depuis le dépôt du rapport Brundtland, le développement durable a captivé l'imagination du public et des décideurs à l'échelle locale, nationale et internationale. Il constitue un objectif souhaitable pour la totalité des personnes, des institutions, des secteurs de l'économie et des sociétés, en fait pour la grande collectivité mondiale. Son concept a stimulé de grands débats à l'échelle mondiale, mais ses modalités d'application ont été peu abordées.

Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry. Victoria, British Columbia, Canada, February 10-12, 1998. D.A. Hill and D.G. Leckie, editors. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia. pp. 367-374.

L'engagement grandissant envers la saine gestion de l'environnement laisse également transparaître l'opinion que l'environnement, y compris ses ressources naturelles, n'est pas un patrimoine que nous ont légué les générations passées, mais plutôt un bien dont la sauvegarde nous est confiée. Par conséquent, les pratiques forestières doivent conserver les capacités de production et de renouvellement des écosystèmes forestiers pour les générations à venir. Il faut également protéger les valeurs non ligneuses des forêts comme la beauté des paysages, les habitats des espèces sauvages et du poisson et les bassins versants.

Tous les responsables de l'élaboration des politiques doivent arriver à concilier intérêts nationaux et responsabilités internationales et à mettre sur pied des institutions et des instruments stratégiques flexibles. Pour pratiquer un aménagement durable des forêts, il faut reconnaître les limites des forêts à supporter des changements environnementaux et gérer l'activité humaine de façon à tirer un maximum d'avantages en tenant compte de ces limites.

CRITERIA & INDICATORS OF SUSTAINABLE FOREST MANAGEMENT

Sustainable development requires that a set of biological and socio-economic indicators be assessed to harmonize social, economic, and environmental goals. One approach to defining and assessing sustainable development of forests is the integration of science and policy in Criteria and Indicators of sustainable forest management. Criteria are conditions or processes by which sustainable forest management is assessed. The Indicators are measures of the conditions or processes of a criterion used to explain and demonstrate sustainability.

The Canadian C&I were developed by a scientific and technical process using open consultation and inclusive methods by people from the federal, provincial and territorial governments, the academic community, industry, non-government organizations, the Aboriginal community, and other groups with an interest in forests. The result of these consultations is an assessment of forest sustainability representing the best available scientific knowledge on the subject in Canada.

C&I provide information on trends in the status of forests and related values over time. Much of the data required for national reporting is provided through current information systems. Where there are no reasonable quantitative measures we use qualitative or descriptive methods to describe and assess indicators. C&I are designed to reflect the range of forest conditions and so may be appropriate for reporting at a national or a provincial level, or for an ecological zone or region. This flexible framework should capture diverse ecological, social, economic and cultural conditions.

How do Criteria and Indicators work now? Canada reports under the CCFM process on 83 indicators and under the Montreal Process on 67 Indicators. These processes are also linked generally to the Helsinki Process which reports on and assesses sustainability on the management unit level reflecting European forest conditions. As a user, the Canadian Forest Service, leads reporting on both systems which have an 80% overlap enabling use of the same data. The criteria and indicators are intended to be reviewed and refined on an ongoing basis to reflect new research, advances in technology, increased capability to measure indicators, and an improved understanding of what constitutes sustainable forest management.

Criteria and Indicators are used also in the certification of forest practices and products. Certification is the application of a sustainable forest management system to a defined forest area to reflect acceptable levels of performance and to monitor progress. There are a variety of certification methods all of which involve processes of on-ground performance and/or the certification of end products. Certification is designed to ensure that sustainable forest management occurs on harvested areas and the products were produced from forests that are managed on a sustainable basis. In certification, a series of criteria and indicators such as are used in the CCFM, Montreal or other international process provides the technical basis of certification.

C&I have been reported on with the publishing of preliminary reports, background documents and technical reports using currently available information from data representing a wide range of sources. At this

point with the preliminary reports done and reports in more depth projected for the near future, it is appropriate to look at the tools available for reporting.

WHAT CAN REMOTE SENSING DO FOR C&I?

Why should we use remote sensing for such a task? We have two broad and related reasons; if we are to report on national level indicators with a national view, and remotely sensed parameters make sense. Even if we had unlimited resources to gather data on a national scale, it would still be sensible to use remote sensing approaches. We need national level methods for the sake of quality assurance and control so that the entire country is evaluated in similar fashion.

The entire job cannot be done using remote sensing; some indicators naturally lend themselves to this method; others do not. We need support through verification on the ground as an essential part of the process. We need to know and understand the limits of the method in different monitoring situations. As the science evolves we will be able to detect increasingly subtle changes in soils and vegetation and so adjust the increasingly sophisticated indicators and assessments.

Following the publication of the reports, we have a breathing space in which to assess future needs and resources. At present if we have data we use it in reporting, and where we do not, (common for many indicators), we use surrogates or descriptions of the indicators and what they mean for sustainability. We have made a good first start, and if we have no other scale upon which to judge our activities, data and reporting from other countries is comparable to our own. In short we seem to be performing as well as or equally badly as other countries.

FIELDS OF APPLICATION AND NEEDS

I have summarized what our needs are from the point of view of the science and policy mix for the C&I. This is not an exhaustive list either in terms of the individual indicators, or the levels of information needed for each, but progress in these areas will enable substantial improvements in how we report in the future. The needs for national level policies in forest sustainability will continue to evolve and we will respond accordingly. We need to be able to delineate and assess indicators, improve the understanding of indicators, and do a better job of explaining indicators. This will require an improvement in data collection, analysis, and synthesis as we improve current indicators and develop new ones reflecting current and future needs.

FOREST AREA/BIODIVERSITY

The sustainable management of forests is supported by the maintenance of the forest land base. Therefore, we must be able to determine accurately the amount of forested area, the types of forest and the area of forest reserved for various uses. We also need to know how much forest land is being removed from the land base and the amount being added as land formerly used for other purposes is reverting to forests. Indicators that fall within this group include:

- 1.1.1 Percentage and extent, in area, of forest types relative to historical condition and to total forest area.*
- 1.1.2 Percentage and extent of area by forest type and age class.*
- 1.1.3 Area, percentage and representativeness of forest types in protected areas.*
- 2.3.1 Mean annual increment by forest type and age class.*
- 3.1.2 Area of forest converted to non-forest land use.*
- 4.1.1 Tree biomass volumes.*
- 4.2.2 Semi-permanent or temporary loss or gain of forest ecosystems, for example grasslands, agriculture.*
- 4.5.1 Surface area of water within forested areas.*

We need to be able to measure changes over time since the changes affect the total land base available for forests and the characteristics of these areas determine the amount of biomass, forest productivity, and the carbon pools in forests.

Forest fragmentation is an important issue affecting harvesting practices and land use change. The fragmentation of forests into small pieces may disrupt some ecological processes and availability of habitat. Some fragments of forest may be too small to maintain viable breeding populations of species. Distances between forest fragments can interfere with pollination, seed dispersal, and wildlife movement between patches of forest. What can remote sensing tell us about fragmentation and connectedness? We may need data at fairly high resolution and measurement over time to measure status, and to detect trends. This indicator should be a high priority for assessment using remote sensing techniques:

1.1.4 Level of fragmentation and connectedness of forest ecosystem components.

NATURAL AND ANTHROPOGENIC IMPACTS ON FORESTS

Forests are influenced to greater or lesser degree by natural and anthropogenic factors; two broadly-based factors that are related. Natural disturbances include the impacts of wildfire, insects, and diseases. We have reasonably good data on these in the extent and impact on the ecosystem largely derived from operational surveys. Recent changes in government policies mean that these surveys are difficult to maintain under current economic conditions. The area affected is relatively easy to determine but impacts also need evaluation and this is less easy to measure. New methods may then need to be developed using remote sensing. We know for instance that an area of resolution of 1 Km would enable us to estimate 95% of the area burned in wildfire but the severity information which has a great implication for sustainability is much harder to come by. Yet we need to know if the area burned and the severity is increasing beyond natural levels.

Areas damaged by insects and diseases are extensive in space and time. Can we determine the range of defoliation levels from trace to severe over time? Low levels of defoliation do not greatly affect biomass production or stand mortality, but levels approaching 30% cause reduced growth. Continued defoliation at these levels causes tree mortality. Are the areas affected increasing and is this a result of management or harvesting practices? Can we distinguish damage from different insects? Insects cause different effects; some cause quick mortality such as the hemlock looper, others (such as the budworms) cause a decline in growth with eventual mortality, others (such as forest tent caterpillar) cause growth losses, but little mortality. These are some of the difficult questions posed in fields where we have relatively good data. Problems will be greater where indicators are less well described. There are implications for adaptive management depending on these results.

Indicators relating to these impacts include:

2.1.1 Area and severity of insect attack.

2.1.2 Area and severity of disease infestation.

2.1.3 Area and severity of fire damage.

Human impacts on forests have become as important as natural ones over the past century through the alteration of forest succession from harvesting and management activities such as fire suppression, and the accidental introduction of foreign organisms which have impacted forests. Alteration of the biology of forest ecosystems has an impact on sustainability and the detection and measurement of these is critical for our understanding of sustainability.

We need to know the area of forest harvested. This we can do now for large areas but forest harvesting in Canada also includes cut blocks, strips, and partial harvests in selection forests. The areas of protected forests along streams and small water bodies is also important. Can we measure and track these? These harvesting patterns are important for sustainability in regional or local situations and for different forest types. Here a resolution of 1 Km may not be enough. A relevant indicator for the harvesting of forests is;

5.1.1 Annual removal of forest products relative to the volume of removals determined to be sustainable.

A similar requirement is the evaluation of regeneration, whether natural or artificial, such as;

2.2.2 Percentage of area successfully naturally and artificially regenerated.

The influence of exotic plants, insects, and diseases are important and may be increasing. With the changes in trade patterns we can expect more introductions of alien species that may pose greater risks to forest biodiversity. Are the impacts from these changes different in appearance from those of native stresses? Can we detect unique damage patterns caused by Gypsy moth or Balsam Woolly Adelgid or Pine False Webworm? The damage may appear subtle but the impact on forest productivity and on biodiversity can be great. How much of this can be evaluated using current or proposed remote sensing techniques?

The indicator most appropriate here is;

2.1.7.1.1 Area and severity of occurrence of exotic species detrimental to forest condition.

FOREST HEALTH ISSUES

Forest health is a major policy area with the issues being - Are our forests healthy? What is changing in our forests and why? How do our forests compare with other similar forests around the globe?

Forest health research, centred on the anthropogenic impacts of changing atmosphere on forests, has been instrumental in the development of national policies on pollution abatement and limitation. This information has been used in supporting the negotiation and implementation of the Canada-US Accord on Acid Rain. Information from CFS and other monitoring networks is used to report on the agreement. Other international policies are being developed on ozone and climate change. The recent discussions at Kyoto which have received so much publicity is an excellent example. To participate in such discussions and to support the commitments arising from them, we need to know what is happening in our forests, and to be able to predict the impacts of the various stresses.

We know that humans are having an impact on forest ecosystems, also that these ecosystems have changed and will change with time and in ways we can seldom predict. Measurement of these changes over time is a great challenge for the remote sensing community.

Air pollutants have a significant cumulative impact on forest ecosystems by affecting regeneration, productivity, and species composition. Correlating forest inventory information with air pollution data can provide information on areas at risk and the potential losses to be expected from current and projected loadings of pollutants. The CFS has an effective research program on air pollution, and monitoring on the ground. This is an opportunity to collaborate with the remote sensing community in the development of new methods.

Is it possible to detect the often subtle and contradictory changes wrought by pollution using new and sophisticated techniques? Is it possible to detect changes in crown transparency and dieback? Our science, monitoring and testing tells us that these factors are related to tree health. For instance, beyond certain levels of dieback, trees will almost certainly die within five years. Can this be monitored to determine the area and severity of the affected forest. Studies are currently underway in Ontario give optimism that remote sensing techniques will soon be developed to detect and monitor such changes. The indicator for this factor centres on;

2.1 Incidence of disturbance and stress, pollution and crown transparency.

The soil resource is a basic component of all terrestrial ecosystems and its loss influences the productivity and composition of forest ecosystems. Forests are particularly important in the regulation and maintenance of water flow and changes in these beyond historical levels impacts the health of forest ecosystems and so on sustainability. Indicators from the Montreal Process assessing these are:

- 4.a Area and percent of forest land with significant soil erosion.*
- 4.c Percent of stream kilometres in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation.*
- 4.e Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities.*

CARBON CYCLES

The maintenance of the forest contribution to global carbon cycles is an important component of sustainability, since forests make a positive contribution to global cycles through the uptake and storage of carbon. The conversion of forest lands to low biomass, short-lived standing crops with rapid turnover rates, or the permanent removal of forest cover reduces the capacity of the land to store and absorb carbon. The accumulation of biomass as living vegetation, debris, peat, and soil carbon is an important forest function and the rate of accumulation is used as a measure of forest health and vitality. Thus the ecological and sustainable management of production forests are factors in controlling the amount of carbon entering the world's atmosphere.

Basic policy questions arise from our consideration of the forest sector carbon pool. Are our forests sources or sinks of carbon, and are changes occurring in the carbon cycle? Different methods are used to provide the science support to these issues; carbon budget modelling is one rapidly-developing method. What can the remote sensing community contribute to this issue? Is there an opportunity to measure and monitor forest growth from space? Simulations developed at the Canada Centre for Remote Sensing indicate a possibility for estimating the carbon budget by evaluating net primary productivity. If this can be done, it will be a useful addition to our estimates of carbon. This will provide increased reliability of estimates, and help reduce the degree of uncertainty that so concerns the policy community.

The recently agreed-to protocols from Kyoto at the meeting of the Conference of the Parties of the Framework Convention on Climate Change means that Canada regards forests as sinks of carbon. Since these sinks are part of our international commitments, we will need the best science available to support policy actions. We realize that the decisions arrived at in such forums must be open and transparent and so based on reliable data. We can expect commitments to change over time and possibly in ways in which we do not expect and cannot control. Therefore we need a research program sufficiently broad to capture these ideas, and enable us to respond. These indicators from the CCFM process also cover similar indicators reported on in the Montreal Process indicators. The indicators to be addressed in this field are:

- 4.1.1 Tree biomass volumes.*
- 4.1.2 Vegetation (non-tree) biomass estimates.*
- 4.1.3 Percentage of canopy cover.*
- 4.1.4 Percentage of biomass volume by general forest type.*
- 4.1.5 Soil carbon pools.*
- 4.1.6 Soil carbon pool decay rates.*

MODEL FORESTS

Model Forests have been established throughout Canada and in several other countries to promote and demonstrate the sustainable management of forests through a co-operative and consensual approach to the management and use of forests. Forest users, owners, and beneficiaries are all encouraged to cooperate and use their talents and ideas to promote and achieve these ends. Within countries and regions, Local Level Indicators (LLI) are being developed to contribute to indicators applied at larger scales, and to provide the basis for assessing sustainability at local or regional scales. Model Forests provide an opportunity to test and assess local level indicators.

The use of LLI while of direct value in the context of Model Forests may not appear to be related to indicators applied to larger areas. However, indicators applied at larger scales are often an aggregation of data or information obtained at local or regional levels. Indicators based on national inventories or forest health monitoring systems are examples. The LLI may also reflect case studies which enhance or explain larger-scale

indicators. Many of the same problems and opportunities apply to Model Forests as to national ones where the needs for accurate and timely information on changes is equally relevant. The opportunities for the use of remote sensing techniques in Model Forests are evident to many people working at these levels. This includes the operational testing of techniques that may eventually be applied at larger scales.

The range of forests and the mix of human activities in Model Forests are representative of our forests nationally, and so trends observed here may explain trends at larger scales such as the Ecozone or national level. Many of the same indicators listed previously can be measured and assessed at a local scale in the Model Forests for use in national indicators.

CONCLUSIONS

Forest management concepts evolve based on scientific knowledge of how forest ecosystems function and respond to human interventions, and to the changing public demands for forest products and services. Criteria and indicators will be reviewed and refined on an ongoing basis to reflect new research, advances in technology, increased capability to measure indicators, and an improved understanding of what constitutes sustainable forest management. Opportunities exist for the application of remote sensing techniques to estimate forest area, impacts on forest condition and health, the carbon cycle, and in the testing of new techniques at the level of Model Forests. The rapidly developing and evolving techniques provide scientists, technologists and policymakers with opportunities and challenges to develop the best available science to support our national and international commitments.

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AUSTRIAN FOREST INVENTORY SYSTEM

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ABSTRACT

In the mid 80's, a new Austrian forest inventory system has been designed. One of the main goals of the system was to establish a reliable method to monitor and recognize changes in the vitality of Austrian forest. A major component of the new inventory system is based on the interpretation of high spatial resolution color infrared aerial images. The key point is to repeatedly gather data about a statistically significant number of individual trees. This is achieved by the use of analytical plotters. A regularly spaced raster grid of default size 500m x 500m is used and a default of 2-3 trees of each species found in the vicinity of each raster point are interpreted. Responding to special requirements, adjustments of these defaults (raster size, number of trees) are possible. The identical individual trees can be addressed in a time series of aerial images taken every other 5 years and changes in the condition of each tree (growth, vitality, damage, cut, etc) can be evaluated. While the routine inventory is run by visual interpretation using analytical plotters, there has also been research in towards possibilities of further automation. Two prototype implementations suggest:

1. Combined visual-digital interpretation with online classification of tree vitality, and
2. Fully automatic tree isolation and classification.

The routine inventory, based on visual interpretation, has been in operation since 1989 and is still being used.

RÉSUMÉ

SYSTÈME AUTRICHIEN D'INVENTAIRE FORESTIER

Au milieu des années 80, on a conçu un nouveau système d'inventaire des forêts autrichiennes. L'un des grands objectifs de ce nouveau système était de trouver une méthode fiable de surveillance et de dépistage des changements de vitalité des forêts autrichiennes. Ce nouveau système s'appuie sur un élément capital, l'interprétation d'images aériennes infrarouges couleurs à haute résolution spatiale. À cette fin, il faut compiler à maintes reprises des données sur un nombre statistiquement significatif d'arbres individuels. Pour y arriver, on utilise des reconstituteurs analytiques. On se sert d'une structure matricielle dont les dimensions par défaut sont de 500 m x 500 m et on interprète un ensemble par défaut de 2-3 arbres de chaque espèce situé non loin de chaque point de la grille. Il est possible d'ajuster ces valeurs par défaut (dimensions de la grille, nombre d'arbres) pour répondre à des besoins spéciaux. On peut examiner ces mêmes arbres à l'aide de séries chronologiques d'images aériennes prises tous les cinq ans et on peut évaluer l'évolution de l'état de chaque arbre (croissance, vitalité, dégâts, coupe, etc.). Les activités courantes d'inventaire utilisent l'interprétation visuelle par reconstituteurs analytiques, mais des recherches sur les possibilités d'une plus grande automatisation ont été effectuées. Deux essais du prototype laissent entrevoir :

1. une interprétation visuelle-numérique combinée, avec une classification en ligne de la vitalité des arbres, et
2. l'isolement et la classification entièrement automatisés des arbres.

La technique d'inventaire faisant appel à l'interprétation visuelle est utilisée régulièrement depuis 1989.

INTRODUCTION

The new Austrian forest inventory system described in this paper has mainly been motivated by observations of rapid decrease of forest vitality in many areas of Europe. 40% of Austria is covered by forest, thus constituting a major economical as well as environmental factor. In the early 80's, a series of several unfavorable years of unusual weather conditions led to a dramatic decrease of forest vitality, where for the first time large areas of Austrian forest became affected. Previous conventional (mostly terrestrial) forest inventory was not able to cope with important questions arising from this new situation. A new inventory yielding detailed quantitative information about spatial distribution and temporal development was required. Such a system should:

- provide information about forest condition of large areas with respect to local conditions (e.g. slope, exposition, altitude, soil, environmental pollution, etc.),
- monitor the temporal development in a relative scale (i.e. compare temporal changes with respect to the previous situation),
- be feasible. Information about large areas should be collected in short time intervals, at high spatial density and at reasonable costs.

Since 1952, the Austrian "Forstliche Bundesversuchsanstalt (FBVA)" has been the Austrian authority responsible for forest inventory. Responding to the requirements described above, in the period of 1984-1989, FBVA implemented a new forest damage monitoring system. This system aims at learning about reasons for forest damage and uses 580 permanent monitoring areas of approx. 1000 m² each. Representative data about condition, location and type of forest as well as of changes are captured at regular intervals. This includes:

- Periodical investigations of the soil (every 5-10 years), e.g. pH value, nutrient supply, heavy metal pollution;
- Annual chemical analysis of needle samples (sulfur, phosphor, main fertility elements);
- Measurements of the concentration of harmful substances (SO₂, NO_x, O₃);
- Annual interpretation of tree crowns from ground level;
- Inventory based on the interpretation of aerial images (all areas are covered completely with a repetition cycle of 5 years)
- And other investigations (e.g. growth analysis by harvesting and measuring selected trees).

While most of these items were implemented directly by FBVA, the inventory based on aerial image interpretation was a separate research project funded by the Austrian Ministry of Agriculture and Forestry. The conception and implementation was carried out by an interdisciplinary research team at the Austrian University for Agriculture and Natural Resources in Vienna. The author of this paper was a member of the team and was mainly responsible for all aspects of digital information processing. The new inventory based on aerial images was developed in 1986-1989 and has been routinely used at FBVA since 1989. The remainder of this paper deals with general aspects of aerial image based forest inventory, while a companion paper (Pinz, 1998) describes in depth the automation of digital image analysis tasks (single tree delineation, species recognition, vitality classification). Since the whole project was a national Austrian affair, many related publications unfortunately are in German. They are nevertheless referenced here for completeness (Schneider, 1989), (Pinz, 1990), (Mansberger et al., 1991), (Mansberger, 1992), (Gelber, 1992).

FOREST INVENTORY BASED ON COLOR INFRARED AERIAL IMAGES

Flexibility was the main goal in the design of a new forest inventory based on remotely sensed data. While it is obvious, that not everything can be seen and judged from an airborne sensor, this is the only feasible solution being able to answer most of the questions raised in the previous section. Furthermore, a very important additional advantage has to be mentioned: The raw images are kept as original data and any future solution/algorithm will be able to use them as a primary source of information in cases where previous computations should be improved or when new questions require new approaches.

In the beginning of the project, many decisions had to be drawn. To mention just the most important ones: Which sensor to use (satellite, radar, airborne scanner, aerial images)? Which spatial resolution is required? In case of aerial images: Which film to use? Which method of data collection and interpretation? Which kind of sample collection will produce the desired results? How should data be organized to make aggregations easy and statistically significant? All of these aspects, and many more, are discussed in detail in (Schneider, 1989). In the following, a brief overview is given.

Color infrared aerial images were selected due to their high spatial resolution, the possibility of stereoscopic interpretation, the suitability to assess vegetation, the exact imaging geometry, and due to rather low costs for data acquisition. In the beginning of the project, a test series of images showing identical areas at the same day, but at several spatial resolutions was taken ending up with images of approximate scales of 1:4000, 1:8000, 1:16000 and 1:32000. It was planned to use Kodak SO 131 film for the project and the test images were mostly made on this film. A few reference images were taken using standard Kodak 2443 film. All the algorithms, interpretations and evaluations developed in the course of the project were tested on this test series with the final result of a scale of 1:12000-1:16000 being optimal assuming Kodak SO 131 film material.

From the very beginning it was clear, that only the evaluation of single trees could yield statistically significant statements. While this is especially true for the Austrian situation, where we find many forest stands with mixed species, it turned out that even in monocultures a completely healthy tree could happen to stand close to a damaged one. Would a sample be drawn from an area covering more than one crown, the result would show all effects of "mixed pixel" problems well known with lower resolution sensors.

There was a unique new idea: It will always be difficult to quantitatively evaluate tree vitality. Even if a good degree of objectivity could be reached either by excellent training of the interpreters or by full automation, there would still remain uncertainty due to variation in capturing conditions, film processing etc. Radiometric calibration was one of the goals of the project but it was open, to which extent it could be reached. The development of trends (e.g.: Does the average vitality of spruce increase or decrease?) was of major interest. This means that time series had to be taken (e.g. capture all areas at least every five years), and the identical tree should be identified in all images. The pragmatic solution for these requirements was to use analytical plotters for image interpretation.

How should individual trees be selected? A regular raster in geographic coordinates (not in image coordinates) is well suited and can be easily supported by analytical plotters. A one-step sampling procedure would simply check, if there is forest at the raster point and then select the tree standing closest to the point. In our project, a two-step sampling procedure was implemented in the following way. First, a regular raster is selected (default is a fixed raster of 500m x 500m over all Austria). Next, at each raster point with forest, trees within a circular area (e.g. 20m radius or 1000m² around the raster point) are selected. Several selection schemes are possible, depending on the requirements of the statistical analysis, e.g.: All trees in the circle; select the *n* trees closest to the center; for each species found in the circle, take the *n* trees closest to the center (e.g. *n*=3).

Finally, for each tree selected by one of the above procedures, a list of attributes was interpreted and stored in a database for later evaluations. There were mandatory attributes (species, vitality), optional attributes (e.g. broken top) and general attributes of the raster point (e.g. slope, exposition). Database requirements and design are described in (Gelber, 1992).

A 3-step implementation of the new interpretation system was planned. Only step 1 was mandatory part of the research grant, parts 2 and 3 were investigated in two dissertations (Mansberger, 1992) and (Pinz, 1988).

1. Visual interpretation.
2. Combined visual-digital interpretation,
3. Automated interpretation.

VISUAL INTERPRETATION

While the scheme outlined above in principle already describes the whole visual interpretation procedure, there are many details which have to be considered very carefully in implementing such a huge project. Most of them are covered in detail by (Schneider, 1989).

Many aspects of such a project will always require manual interactions of human experts with the system, independent of the degree of automation achieved. Examples for such requirements in the pre- and postprocessing are:

- **Flight planning:** In order to cover all of Austria's forest area at a scale of 1:16000 with at least 60% overlap, approx. 25000-30000 color infrared aerial images have to be taken. Image acquisition will be restricted to a rather short season of vegetation in full vitality (mid June – mid September). August would be optimal to detect forest damage. Sun incidence angle should be above 50° and sight should be excellent with additional requirements of clear sky, which further restricts the applicable time slot
- **Ground truth collection:** Radiometric calibration of the images requires radiometric reference data to be taken at exactly the time and location of the image acquisition flight.
- **Judgement of image quality:** The capture of images which are not suited for later interpretation has to be repeated.
- **Homogeneity and significance of interpretation results:** Such a huge project requires the collaboration of a team of interpreters. This immediately raises questions of differences in judgement, proper training, personal trends, elimination of outliers etc.

In the beginning of the project, all interpretation and training tasks were allocated to an experienced photointerpreter in the team. This person was responsible for the elaboration of an 'interpretation key' consisting of many typical examples. Each page of this key contained a small pair of images which could be viewed stereoscopically, and a hand drawn map of the situation including tree crowns, species, and vitality assessment (see fig.1 for an example). Training and judgement of interpreter performance was assisted by several evaluation tools calculating aspects like reliability, comparability, and personal trends. This was achieved by presenting the same images to more than one interpreter (comparability), by requesting interpretation of images where ground truth was available (reliability), and by facing a specific interpreter with the same image several times during the course of the project (e.g. every month, personal trend evaluation).

Analytical plotters with the additional feature of 'graphical overlays' were used (see fig.2 for the typical setup). The core part of visual interpretation was made up of the following steps:

1. Insert a pair of color infrared aerial images in the analytical plotter;
2. Perform orientation of the images;
3. The system automatically positions to the next raster point (500m raster). The raster point is visualized in a graphical overlay. If forest is very homogeneous, the interpreter can decide to subsample the raster (e.g. 1km x 1km), if important peculiarities are found, he can select a supersampling mode (e.g. 250m or 100m raster). There is further possibility of manual interaction / supervision of the raster based inventory: The interpreter can manually position to any object of special interest in the image and enter additional 'special trees';
4. The interpreter decides, if there is forest found at the raster point. If not, go to step 3;
5. Generic attributes for the raster point are entered (slope, exposition, type of forest, etc.) and stored in the database;

6. The interpreter selects a tree and adjusts the position to the top of the crown. This operation again is supported by feedback in the graphical overlay marking the selected tree;
7. Specific attributes of the selected tree are entered (species, vitality, size, crown radius, special attributes) and stored in the database;
8. If the required criteria mentioned in the previous section (e.g. number of trees per species) are not yet fulfilled, and more trees should be selected at this raster point, go to 6;
9. If there are more raster points to be interpreted, go to 3.

The above steps describe an initial interpretation when a raster point is addressed for the first time. The procedure is different for a re-interpretation of the same point in a time series (typically of a new image pair taken 5 years later). In this case, the system performs step 3 and shows the stored attributes of the raster point for acceptance or for modification. Next, steps 6 and 7 are performed automatically, i.e. the system tries to position on top of each tree crown and displays the attributes stored for this tree. Manual adjustments have to take place (e.g. adjust tree height, change certain attributes) before the next tree will be addressed.

COMBINED VISUAL-DIGITAL INTERPRETATION

The 'combined visual-digital interpretation system' is described in detail by (Mansberger, 1992). The main idea is to use the manual procedure described in the previous section, but to try to automate those steps where a better result can be expected. 'Better' in this context means more objective (interpreter independent), reproducible, and faster interpretation by incorporation of digital image analysis steps. The previously described analytical plotter system is augmented by a special purpose unit which is capable of real time digitizing of rather small portions of an image in the current central fixation area (i.e. typically the crown of the tree currently under inspection). This is achieved by using a semitransparent mirror in one of the two beams reflecting a portion of the light towards a CCD-camera and a filter wheel. Thus, multispectral digital raster images can be obtained online. A schematic diagram of the complete system configuration is given in fig.3.

While steps 1 to 6 in the above procedure are still carried out by the human operator, step 7 is now augmented by digital image analysis. The human interpreter manually enters all attributes described in step 7, and the CCD camera captures a 512 x 512 color image. Depending on the given attributes (tree species, crown diameter, position in the image), the original image is reduced to a color pixel matrix of 64 x 64 pixels representing the center of the crown. Depending on the type of tree (coniferous / deciduous) and its position in the aerial image (center / periphery), different tree models and pixel schemes are employed to define a mask. This mask is refined taking radiometric information into account (especially the masking of shadow areas). Finally, an application of the mask reduces the original pixel matrix to a subset of highly relevant pixels of the crown under investigation. This whole procedure is illustrated by fig.4-fig.10.

Based on the remaining pixels in the masked 64 x 64 grid, several features are extracted and stored in the database and used for a subsequent automatic classification procedure determining tree vitality.

AUTOMATED INTERPRETATION

The rough description of the rather complicated 'combined visual-digital' approach, where still a full workload for the human interpreter is involved, motivates the search for further or possibly full automation of the complete interpretation process. Research in this area was carried out by the author of this paper and has been described in several other publications. A review on automated tree isolation and species recognition is given in a companion paper in this proceedings (Pinz, 1998).

In the manual interpretation steps described previously, there are several operations which are difficult but do not require much effort (e.g. orientation of the images, decision if forest is present at the raster points). These operations should still be performed by human operators, e.g. in an initialization phase. Other parameters (e.g. slope and exposition at each raster point) could be obtained by a completely different kind of processing, e.g. from a digital elevation model. But there are processes which are very tedious and have to be repeated all the time, but are substantial for all subsequent operations:

1. Finding a single tree (crown center coordinates),
2. Estimating the crown radius,

3. Classifying tree species,
4. Estimating tree vitality.

Consequently, the development of fully automated interpretation methods concentrated on the above four issues. Details are given in the companion paper (Pinz, 1998). A vision expert system called VES was responsible for tree finding and radius estimation. Species classification and tree vitality estimation was achieved by neural network classifiers.

RESULTS AND CONCLUSIONS

In the early 80's, upcoming new forest damage phenomena in wide areas of Austrian forests set the demand for a new forest inventory with special emphasis of forest vitality classification and assessment of changes in forest state. A new forest damage monitoring system was implemented and one important component of this system is a new inventory based on the interpretation of aerial color infrared images. This aerial image interpretation system was topic of a major interdisciplinary research effort in 1986-1989. Since 1989, the whole new monitoring system, and also the visual interpretation system described in section 2.1 have been operational and they are still being routinely used.

The new inventory has many unique features, which enable the very flexible use of data acquired and processed so far. The aerial images themselves serve as an analog storage medium and can be used for future evaluations based on new forest assessment algorithms or in case of new questions arising. Since many images show also non-forest areas, they can be of use in completely different application domains (e.g. land use classification, monitoring of changes, e.g. construction activities, updating of maps etc.). Interpretation data have been stored in a database and are carefully and flexibly organized at several levels of aggregation (raster point, forest stand, district, state). Due to this organization, many kinds of questions can be answered with sufficient statistical significance.

Many problems of huge inventories have been addressed and solved in the course of this project, e.g. the training and the homogeneous operation of a large team of photointerpreters, or the radiometric correction of color infrared aerial images. A major contribution was the idea to use analytical plotters to reliably find a specific tree in several time instances of an inventory which may last for decades.

Aspects of full automation of an inventory process were investigated at two different levels of abstraction. Rather simple three-dimensional tree models together with the possibility of online capture of digital images have led to more objective and reliable tree vitality classification (but have not been used routinely in the project). Forest scene interpretation based on high resolution aerial images has led to the development of a prototype system. An expert system component is responsible for tree finding and delineation and a neural network for species and vitality classification. This prototype system also has not been used routinely in the project. Experiences with both levels of automation have indicated problems of the approaches as well as future directions of research. Two of these aspects should be mentioned here explicitly: It would be better to use the stereo pair and to incorporate 3D reconstruction and knowledge about the 3D structure of a tree; modeling of 'common sense' would be required in many cases, e.g. the understanding of logging roads, cuts, or other special situations.

There is feedback from FBVA about their experiences in routine use. They report on excellent suitability of the visual interpretation system. Since 1989, 25 projects were carried out, a total area of approx. 10.000 km² was interpreted, including 100.000 individual trees and 10.000 aerial images. The original concept of an inventory completely covering all Austria has been given up. Instead, smaller areas are investigated at greater detail (e.g. raster sizes of 250m or 350m), with an average of 8-9 individual trees at each raster point. A main reason for this change was that Kodak has stopped the production of the SO 131 film material. With SO 131, scales of 1:15000 would have been suitable, now standard Kodak 2443 has to be used at a scale of 1:7500. The efforts for a complete covering of Austria at this scale are not justified.

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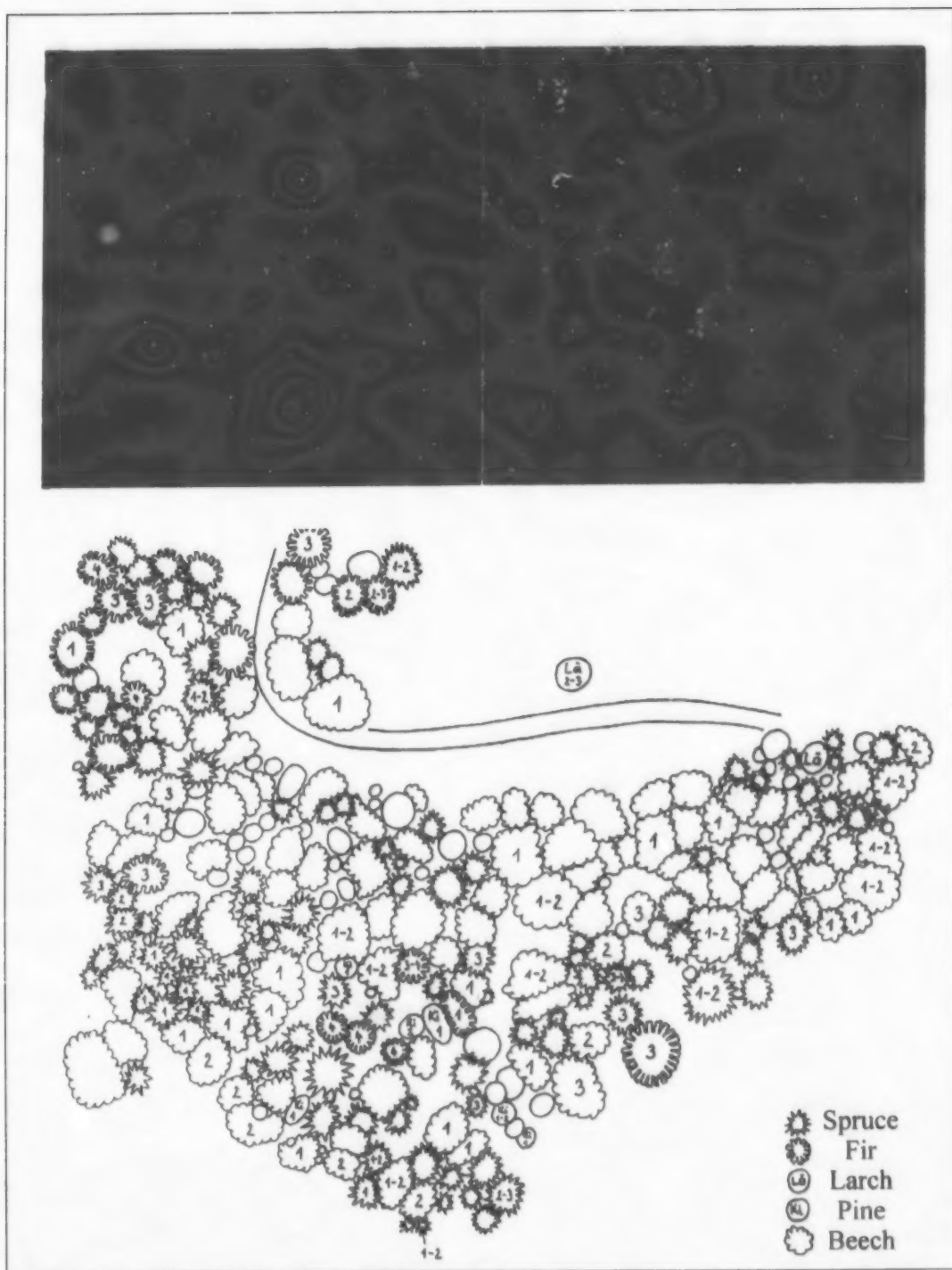


Figure 1: Example of an "interpretation key" used for the training of interpreters (from Schneider, 1989). The stereo pair on the top can be viewed stereoscopically, the hand drawn map indicates tree species and vitality.

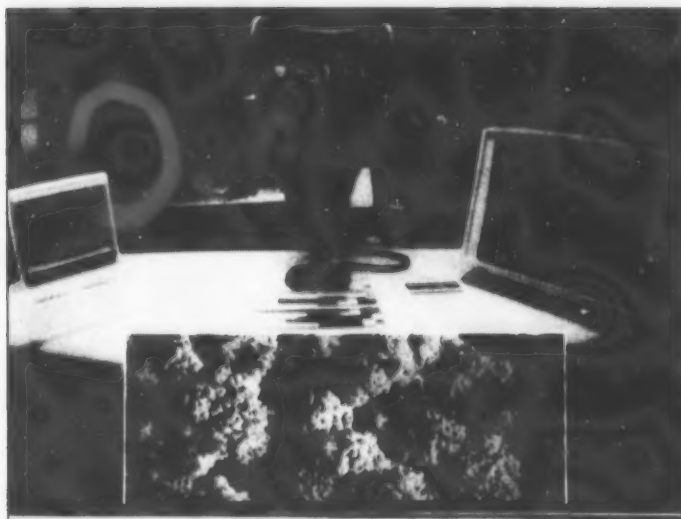


Figure 2: The typical setup of the analytical plotter used for visual interpretation. See also (Mansberger, 1992) and (Pinz, 1990).

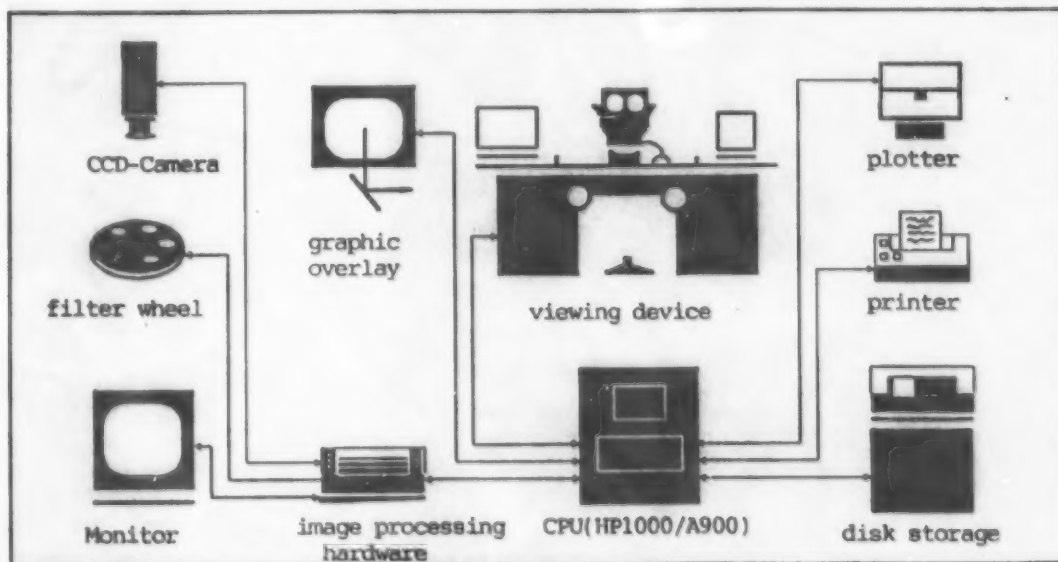


Figure 3: Overall system configuration including CCD camera and filter wheel for combined visual-digital interpretation. The graphic overlay is required for visual feedback (raster points, trees, etc.). (from Mansberger, 1992).

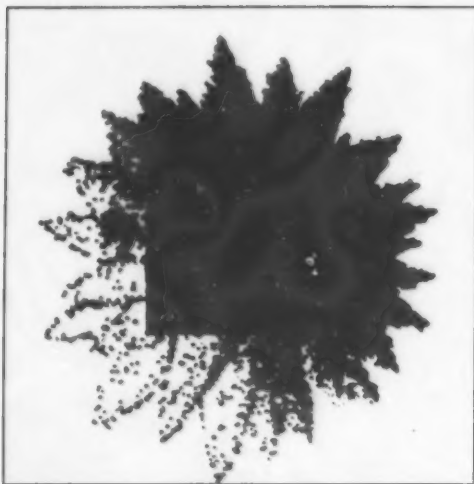


Figure 4: The pixel matrix for a coniferous tree in the center of an aerial image (from Mansberger, 1992).

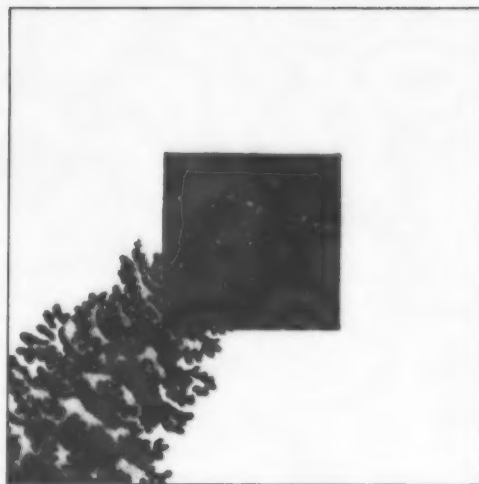


Figure 5: The pixel matrix for a coniferous tree at the periphery of an aerial image (from Mansberger, 1992).

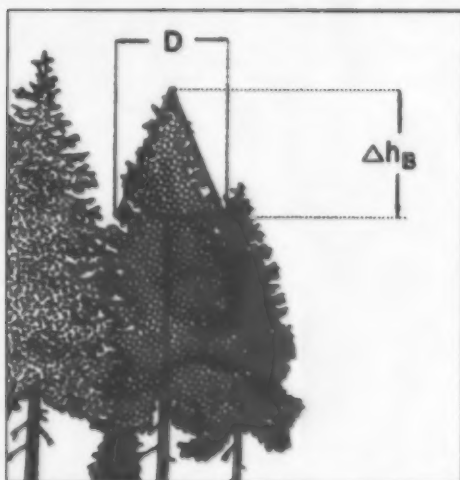


Figure 6: Crown model for a coniferous tree (from Mansberger, 1992)

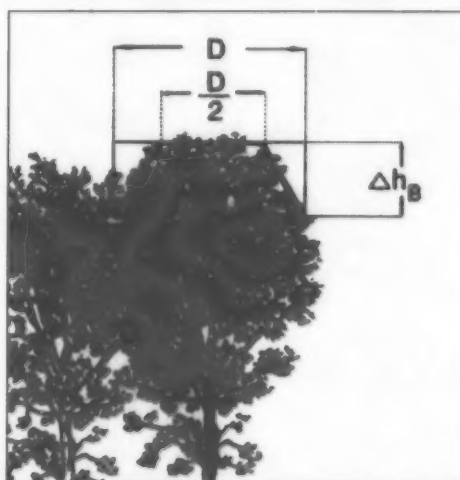


Figure 7: Crown model for a deciduous tree (from Mansberger, 1992).



Figure 8: Pixel matrices of 49 coniferous trees before masking. Each crown is represented by 64×64 pixels. (from Mansberger, 1992).



Figure 9: The matrices from fig. 8 after masking based on estimating the geometric crown model (from Mansberger, 1992).

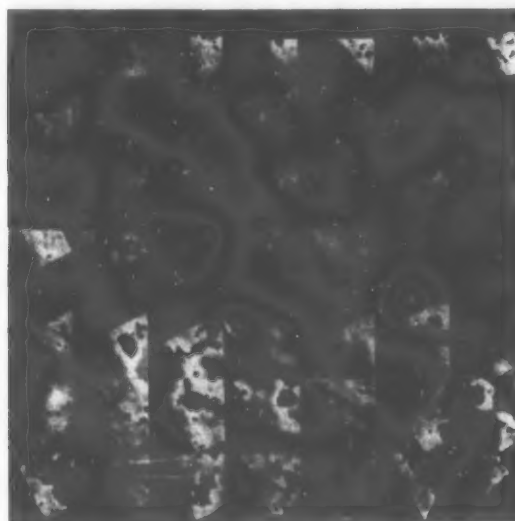


Figure 10: The matrices from fig. 9 after masking based on radiometric selection of pixels. These images are the final input for feature extraction and classification. (from Mansberger, 1992).

AUTOMATED STREAM PLANFORM MAPPING: A TEST STUDY

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ABSTRACT

The nature of streams and their fish habitat is now a critical parameter to forest management. Mapping of the main features of stream courses is valuable baseline information for channel assessment and fisheries surveys, determining stream classes for prescribing logging setbacks and monitoring changes over time due to natural events or logging activity.

Eighty centimeter casi imagery was acquired over Tofino Creek on the west coast of Vancouver Island, British Columbia. Using a spectral angle mapping algorithm, seven surface types were classified (deep water, shallow water, sand, gravel and cobble, woody debris (e.g., logs), conifer and deciduous). Comparison with ground truth taken within days of the imagery indicates general agreement of surface types and accuracy estimations greater than 80 percent for most classes. Individual logs and piles of woody debris were consistently detected. Problems do arise within shadowed areas, boundaries of stream features and forest and with some zones of sand, gravel and cobble.

Keywords: remote sensing, stream, multispectral imagery, casi, high resolution.

RÉSUMÉ

CARTOGRAPHIE AUTOMATISÉE DE LA MORPHOLOGIE DES COURS D'EAU: UNE ÉTUDE EXPÉRIMENTALE

La nature même des cours d'eau et les habitats qu'ils constituent pour le poisson sont désormais des paramètres dont il faut tenir compte dans l'aménagement des forêts. La cartographie des principales caractéristiques des cours d'eau fournit des informations de base utiles pour l'évaluation des chenaux, pour la réalisation d'études sur les pêches de même que pour la classification des cours d'eau aux fins de la prescription des limites de coupe et la surveillance des changements temporels dus aux phénomènes naturels associés à l'exploitation forestière.

Une imagerie de 80 cm du ruisseau Tofino, sur la côte ouest de l'île de Vancouver, en Colombie-Britannique, a été acquise au moyen d'un spectromètre imageur aéroporté compact (CASI). À l'aide d'un algorithme de cartographie angulaire spectrale, on a procédé à la classification de sept types de surfaces (eaux profondes, eaux peu profondes, sable, gravier et galet, débris de nature ligneuse (p. ex., grumes, conifères et feuillus). La comparaison des images et des données de vérité-sol, recueillies quelques jours après l'acquisition des images, révèle une correspondance globale des types de surfaces ainsi qu'une précision d'évaluation

supérieure à 80 % pour la plupart des classes. Les grumes et les amas de débris ligneux sont systématiquement détectés. Cependant, les zones ombragées, les limites cours d'eau-forêt et certaines zones de sable, de gravier et de galets posent des problèmes.

INTRODUCTION

Consideration of streams in forest management is now mandatory and a sensitive environmental issue. Their presence, location, nature, and fisheries habitat are key. A number of important considerations lead the need for information regarding streams:

- a) In many jurisdictions there are requirements to map the stream course and its nature. For example, in coastal British Columbia, the location of this study, detailed requirements and procedures regarding stream channel assessment are set forth by the Forest Practice Code Act, Channel Assessment Procedure Field Guidebook (1996). Channel morphology and disturbance level are described with water depth, riffles, bars, pools, sediment or substrate material, bank morphology and nature of woody debris being important diagnostic keys. The mapping and assessment is done both from aerial photography and the ground. Where riparian vegetation or shadow obscures the stream channel on the air photos, assessments are by necessity conducted on the ground.
- b) The sediment available for transport is important environmentally and from an engineering point of view. Here the volumes of sediment are important.
- c) Debris obstructions and debris available for transport is another important consideration. The main concern is large woody debris either as piles or individual pieces. Potential for serious blockage of stream channels or sudden release of large quantities of debris is a major factor.
- d) Riparian zone management requires information on streams. For example, in British Columbia the width of the logging reserve zone around streams is partially dependent on the presence or absence of fish and channel width.
- e) Fisheries management is closely allied with forest management. Fisheries surveys need to determine quantities of different habitat and to define and sample for fish within reaches. Gradients and obstructions to passage of fish are key.
- f) Perhaps one of the most important considerations in stream management is monitoring of changes in the stream due to various causes. Stream channels change seasonally, gradually over time and suddenly due to flood and high flow conditions. Channel changes, bank erosion, debris accumulation and channel obstructions are the changes of most interest. Knowledge of typical changes in stream condition is useful, but surveys of streams after catastrophic events like flooding would be more urgent. Here a quick method to classify and map changes would be effective. A potentially important issue is in monitoring the effects or lack of changes due to logging operations. Knowledge of typical changes, conditions before logging, and those during and after logging are of interest to both forestry companies, government agencies and environmental interests to determine if indeed logging operations are having or did have any effect.

The above applications areas have important common elements and lead to certain requirements for any method developed to map stream characteristics. Gradient is a critical element. This requires a stereo sensor or extraction of gradient from other sources such as topographic maps or laser altimetry. Defining and then describing stream characteristics within a stream reach is a standard survey technique. There is a common set of surface classes and stream parameters which recurs for many of the applications. Water depth and flow are important with pools, riffles and runs being defined and deep and shallow water identified. Sometimes actual depths are required. Substrate material is classified often as: fines (clay, silt, sand), gravel (small and large), cobble (small and large), boulder or bedrock. Other features such as in-stream and over-stream vegetation and

large organic or woody debris are factors. Stream width in terms of bank full width, average width, wetted width is a common measured feature.

The applications and requirements lead to a need for high spatial resolution in any aerial survey technique to help the mapping of the surface characteristics of streams (stream planform mapping). Aerial photography is often used as a base for mapping. Digital imagery such as airborne video and digital frame cameras are beginning to be investigated and used, but mainly for visual interpretation as is done with aerial photography. This study, through a test study, explores the merit of high spatial resolution multispectral imagers for this application and whether automated classifications/interpretations can make the process more useful. For example, for some monitoring quick analysis and turn around might be important and automated image mosaicing, geocoding and classification would be advantageous.

STUDY SITE, IMAGERY AND GROUND DATA

STUDY SITE

The study site is Tofino Creek, British Columbia, Canada (49° 12' N; 125° 36' W), a typical west coast mountain stream in the Clayoquot Sound area of Vancouver Island. The study area consists of a 5 km length from tidewater to the start of an upper more mountainous stream portion. The rise is 250 m and channel widths range from 10 to 40 m. The stream has some straight reaches but generally follows a sinuous course. Mountains rise fairly steeply on both sides of the stream valley. Substrate material varies from sand, through cobble and some boulder and bedrock. Stream edges are usually surrounded by mature coniferous trees (e.g., western hemlock (*Tsuga heterophylla*); amabilis fir (*Abies amabilis*); Sitka spruce (*Picea stichensis*); western redcedar (*Thuja plicata*)) and some deciduous trees and shrubs with some regenerating areas nearby.

IMAGE DATA

The imagery was acquired by the casi airborne imager on September 25, 1996. The casi sensor is a versatile imaging spectrometer (Anger et al., 1994) which in this case recorded imagery at 80 cm resolution in eight spectral bands (438 nm, 489 nm, 550 nm, 601 nm, 656 nm, 707 nm, 782 nm and 847 nm with spectral bandwidths of approximately ± 25 nm). The imagery was not obtained at higher resolutions due to flight safety considerations in the mountainous terrain. Four adjacent and overlapping flight lines were flown to acquire coverage of the stream course. The imagery was geometrically corrected to an orthoimage using differential GPS, aircraft attitude data and existing British Columbia 1:20 000 topographic map (TRIM) data. Data acquisition and geometric correction was done by Itres Research Ltd., a partner in the project. The imagery was then mosaiced together. The data used in the analysis of this paper was from a section of the stream which was covered mainly by data from one flight line (Figure 1).

GROUND DATA

Ground data was collected September 26 and 27, one and two days after the casi overflights. Over 70 locations were visited along the stream course. At each location 35 mm colour photographs were taken of the channel features. As well several detailed plots were gridded and mapped for surface type. From this information surface conditions were determined for selected areas on the imagery. Water depth (deep, shallow, riffle), substrate material (sand, gravel, cobble, boulder or bedrock) and woody debris (large or small scattered), and surrounding forest condition were assessed. Some finer differentiation of gravel and cobble sizes was done.

METHODS

Automated classification was accomplished in a multiple step process. First the water of the stream was classified with PCI EASI/PACE software and a 30 m buffer from the stream edge created. This created a strip of data for subsequent stream analysis which incorporated only the area around the stream channel. Next, a hierarchical supervised multispectral classification was conducted to extract seven surface types (deep water, shallow water, cobble and gravel, sand, logs and debris, conifer and deciduous). A spectral angle mapper

approach (Kruse et al., 1993) using six spectral bands was utilized and implemented with ENVI software. Pixels and groups of pixels of each class distributed throughout the study area were chosen to generate the reference spectra for each class. Threshold spectral angles around each class were determined through an iterative trial and error process. The classification results were reviewed and areas of confusion between classes were then separated into additional classes. For example, areas of cobble, sand or water under the shadow of trees were initially misclassified, but new classes and reference spectra were created (e.g., shadowed cobble). Through this hierarchical approach a reasonable automated classification was produced.

Classification results were assessed both quantitatively and qualitatively. Fifty sites were selected from the ground photo locations and gridded plots. These sites were of the five stream classes (deep water, shallow water, cobble and gravel, sand, logs and debris). The surface type as determined from the field photos and notes was compared to that of the classification. Classification results from this preliminary analysis were compiled. In addition the classification was visually inspected for errors. Particular attention was paid to classification performance in shadowed, boundary or transition zones.

RESULTS AND DISCUSSION

Classification results (Figure 2) were generally good. Quantitative results on the limited and preliminary set of test sites indicates accuracies generally in the 80 percentile range with an 84% average class accuracy over the five stream classes. Shallow and deep water were classified at 80% and 88% respectively. The log and debris areas were classified at 87% accuracy. The sand test areas were classified correctly but there was commission error with some test sites of cobble/gravel and debris being classified as sand. Commission errors were not a problem with the cobble/gravel class, but only 64% of the cobble/gravel test areas were classified correctly. Errors were with sand, debris, deep and shallow water classes. However, some of this error were areas within the shadow of trees.

Visual inspection also indicates good results. The shallow and deep water classes seem solid. The sand to gravel boundary is gradational and some overlap in the classifications is expected, but nevertheless the classification of the sand and cobble/gravel classes is good. The logs and debris class detected the logs well and even zones of scattered small woody debris. However, it was observed that some zones at the boundary between the stream channel and shrub vegetation at the stream edge were incorrectly classified as debris. The hierarchical classification system seemed to have classified reasonably well in shadowed areas, but as noted in the quantitative results, there were misclassifications within shadows.

Results are good both from a quantitative and qualitative point of view. Finer classes need to be tested, especially within the gradation in grain size from sand, through gravel and cobble. More test sites need to be utilized and results tested over a wider segment of the study area and over more than one flight line of data. Procedures and errors within shadow and boundary zones need more investigation. Preliminary tests of the procedure with similar *casi* imagery over a selection of other streams on Vancouver Island seems to indicate that methods are transferable, but again further testing is needed.

CONCLUSION

A useful mapping of stream surface types was accomplished with automated classification of high resolution *casi* imagery. It remains to be seen if finer surface classes can be differentiated and how reliable and widely applicable the techniques are. Important gradient information could be obtained digitally through the use of airborne laser altimetry. It is hoped that automated stream planform mapping with *casi* or other high resolution multispectral imagers will become a tool available to be utilized by those interested in mapping as they see fit to meet their specific needs.

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Figure 1. 550 nm image of test subsection of the study site. Letters indicate locations of the ground photographs of Figure 3.



Figure 2. Classification product (deep water = dark blue; shallow water = light blue; cobble and gravel = gray; sand = light brown; logs and woody debris = dark brown; coniferous = dark green; deciduous = light green).



a)



b)



c)

Figure 3. Photos of different substrate material along Tofino Creek; a) sand, gravel and small woody debris; b) cobble, shallow and deep water, woody debris; and c) gravel, woody debris and shallow and deep water. See Figure 1 for the location of these photographs.

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